Heavy Ion Fusion

An overview of the program and its computational science*

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UC Berkeley Computational Engineering Science Seminar

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Rosette Nebula

Talk Outline

- Fusion
  - Introduction
  - The Heavy Ion Fusion program
- Modeling plasmas and beams - taxonomy of methods
- HIF experiments and simulations
  - Non-neutral beams in accelerators
  - Neutralized beams in plasmas
  - Targets
- The next step - NDCX-II

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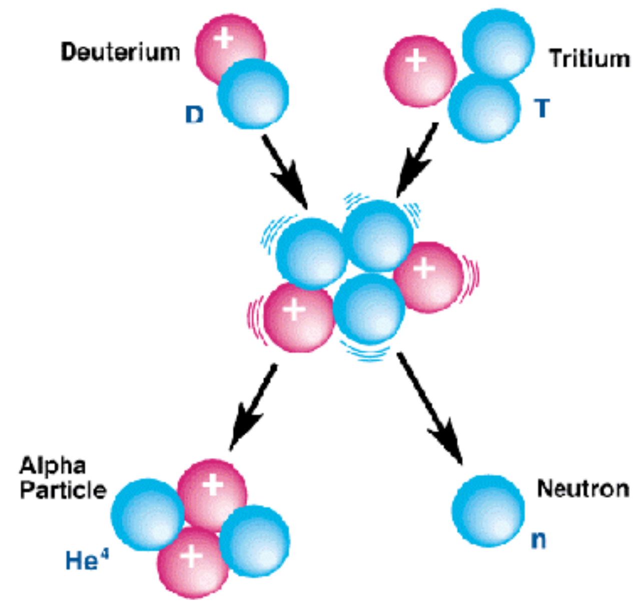
How can we address energy and climate challenges?

- Population growth roll-off (education, economics, …)
- Conservation (more efficient vehicles, buildings, appliances, …)
- Innovation in industrial processes and materials
- Solar, wind, biofuels, …
  not concentrated, use lots of land
- Fission (nuclear power plants, A-bombs)
  radioactive waste, proliferation
- How about Fusion (the sun and stars, H-bombs) ???

Fusion is (potentially) an attractive energy source



Supply:

- Plentiful fuel

Environment:

- No CO_2 & no air pollution
- No radioactive waste from reaction
- Relatively short half-life for components

Safety:

- No weapons material produced
- Nuclear accidents impossible

Fusion energy requires plasma conditions

To fuse, nucleii must:

- Overcome electrostatic repulsion - requires energy (millions of degrees)
- Sufficient number and rate of interactions - requires many particles

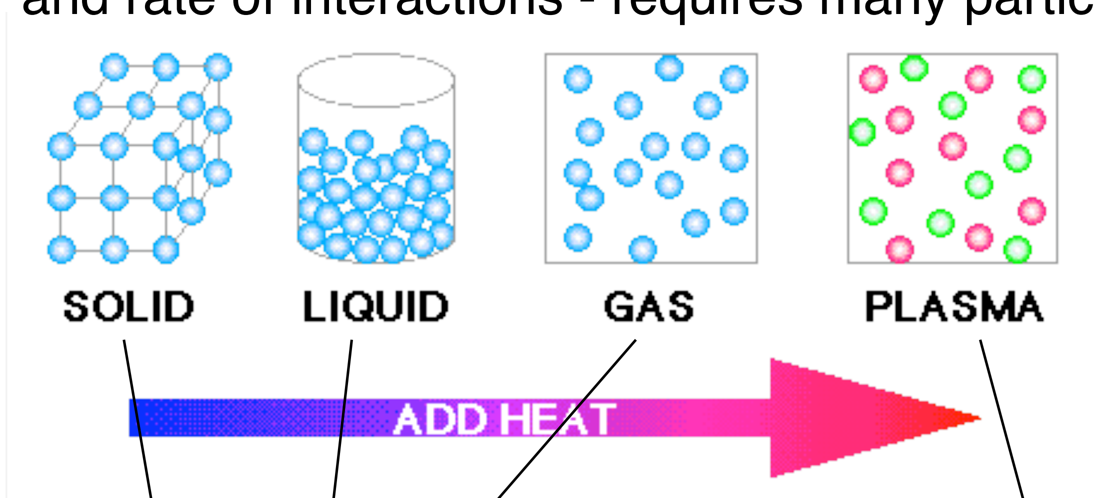
Lawson criterion:

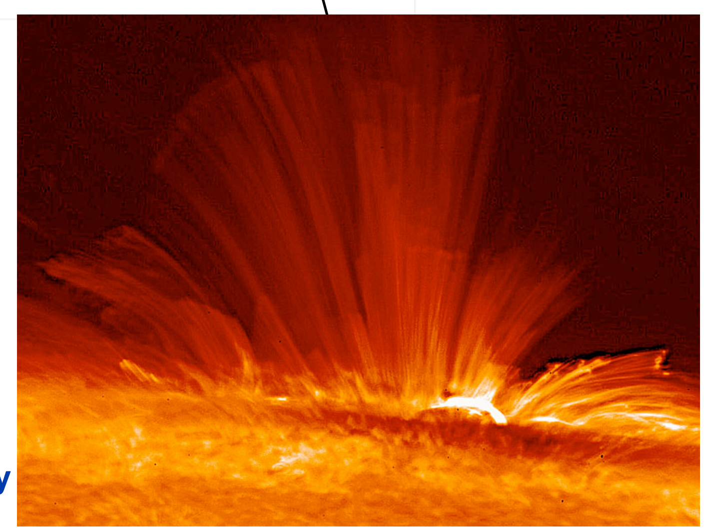
$n\,\tau > 10^{14}$ s/cm^3

Temperature:

$T > \sim 10$ keV

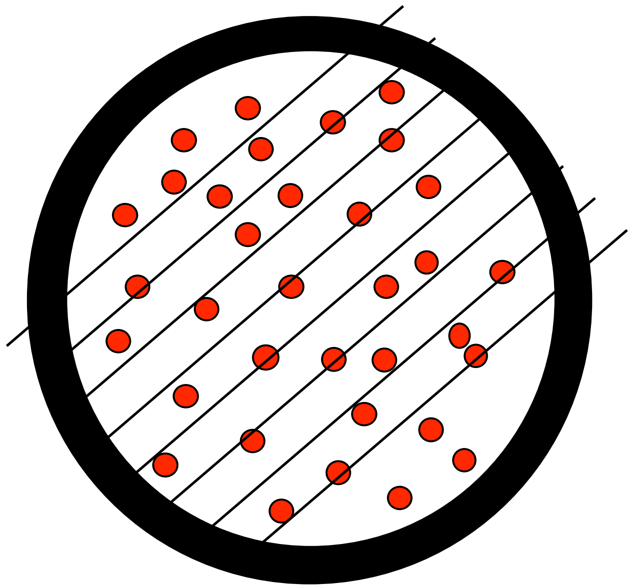
~ 100 M °C





Two Approaches to Fusion

Magnetic Confinement



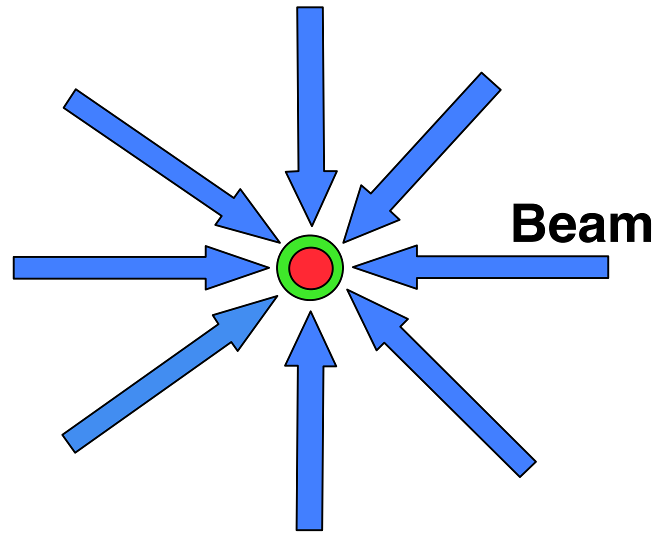
Fuel: D + T Gas

Cycle: constant, or few minutes

Meters in radius

$n\tau T > 10^{15}$ keV-s/cm^3

Inertial Confinement



Fuel: Solid D+T

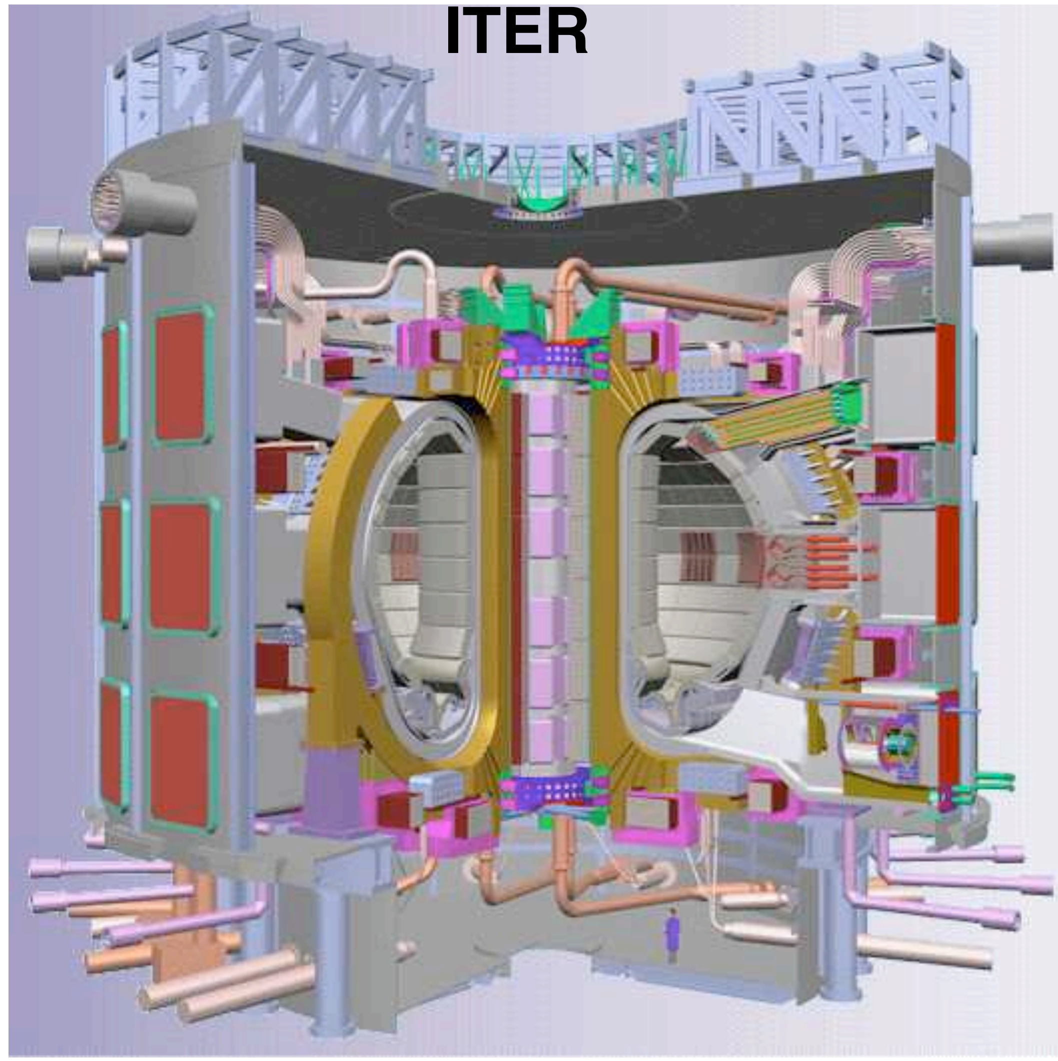
Cycle: 5 times per second

Few millimeters radius

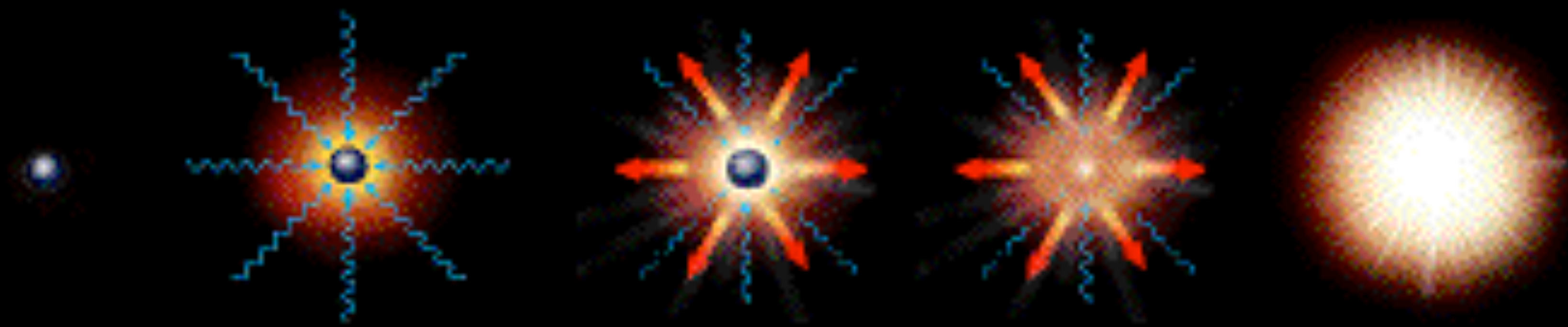
$\rho R > 1$ g/cm^2

The world is exploring "magnetic fusion energy" (MFE)

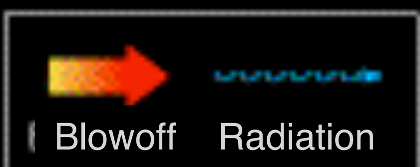
- ~ $250 M/year in US alone (far more worldwide)
- Plasma confinement is the main topic being studied
- Complicated system to maintain; driver, blanket, chamber not separable; "first wall" is exposed
- Short DT burn ~2020; full noninductive drive ~2023



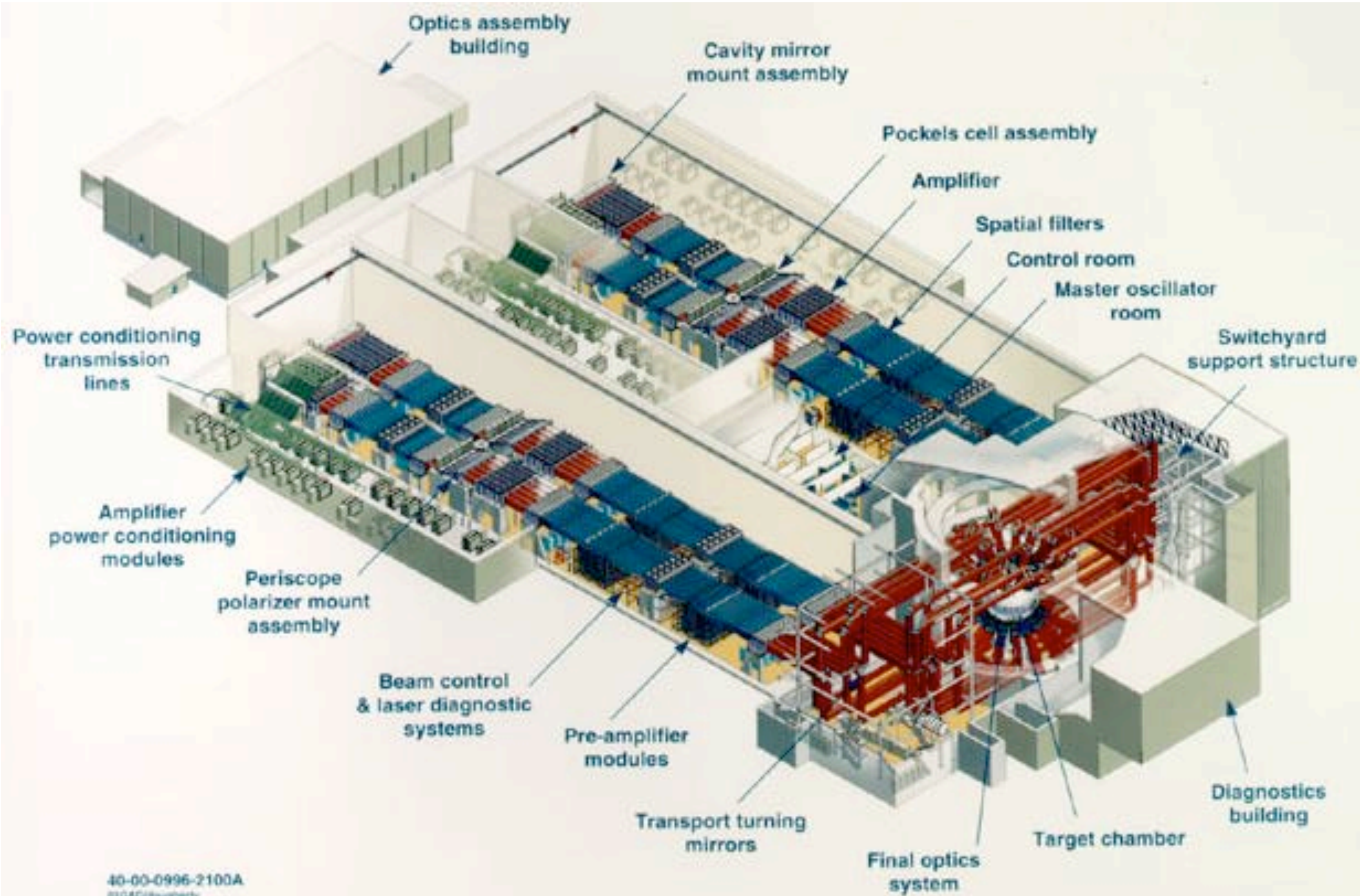
Inertial Confinement Fusion Concept



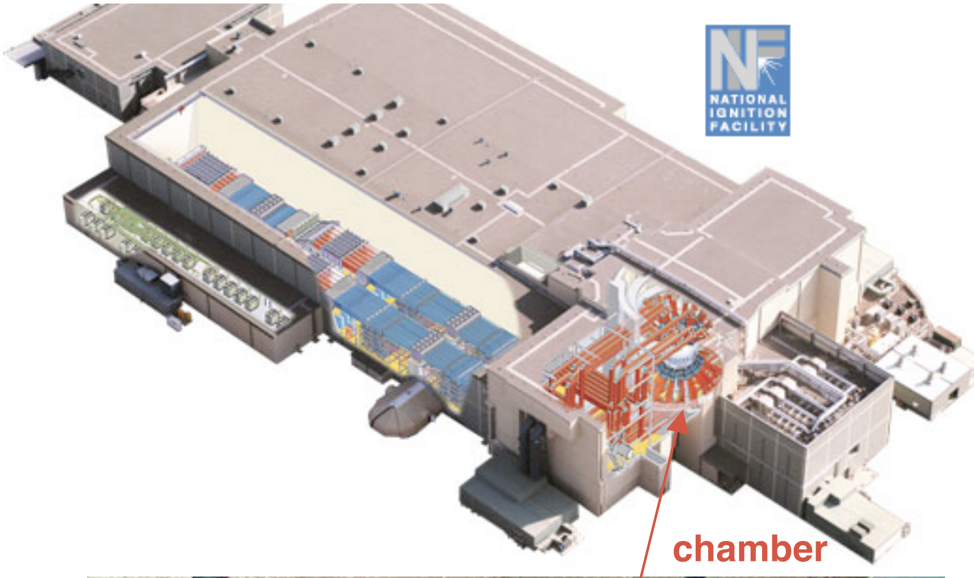
Fuel Capsule	Target Heating	Compression	Ignition	Burn
A small metal or plastic capsule (about the size of a pea) contains fusion fuel	Radiation (light, X-rays, ions, or electrons) rapidly heats the surface of the fuel capsule	Fuel is compressed (imploded) by rocket-like blowoff (ablation) of the surface material	With the final driver pulse, the fuel core reaches about 1000 times liquid density and ignites at 100,000,000 degrees	Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the imput energy

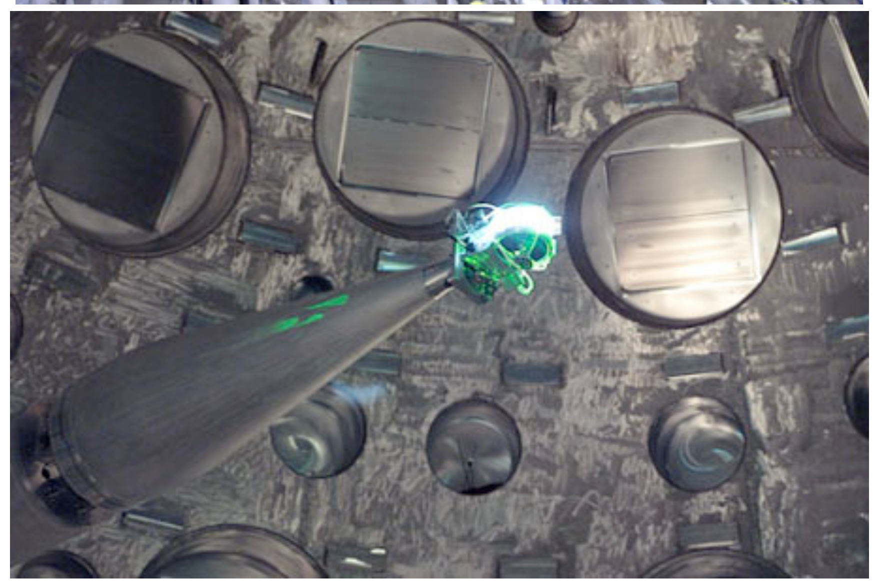


The National Ignition Facility at LLNL is scheduled to complete first "ignition campaign" by 2011

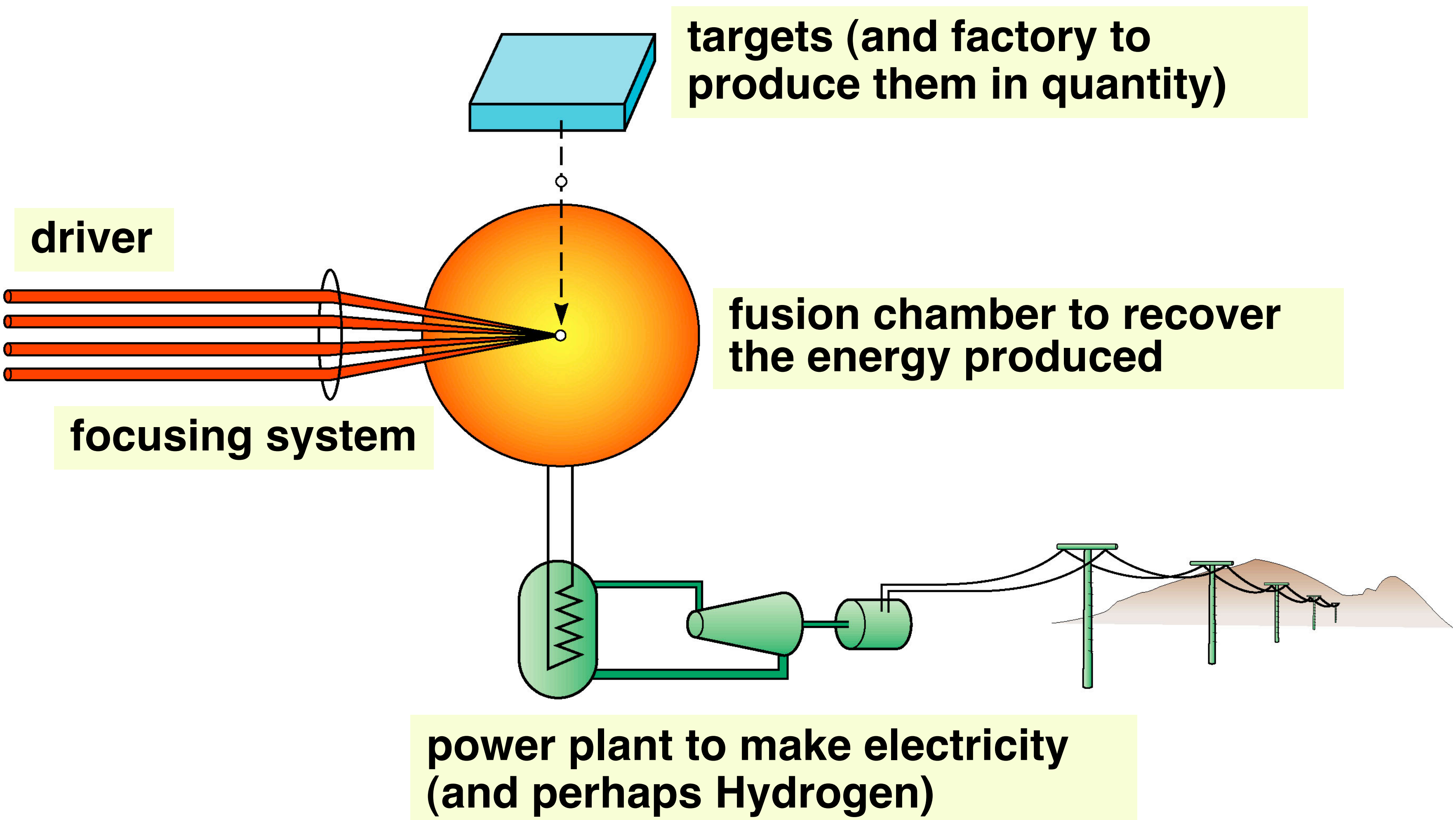


NIF and LMJ in France are of unprecedented scale





Inertial Fusion Energy (IFE) concepts are modular, and differ significantly from Magnetic Fusion Energy concepts



Lasers vs. Ions

Lasers:

Easy to focus

Much more money in program

Easier development path (beams don't interact)

but:

Problem protecting final optics
Problem protecting first wall
All

Low repetition rate (a few/day)
Low electrical efficiency (a few - 10%)
Glass lasers

Cost (DPSSL)

Lifetime (KrF)

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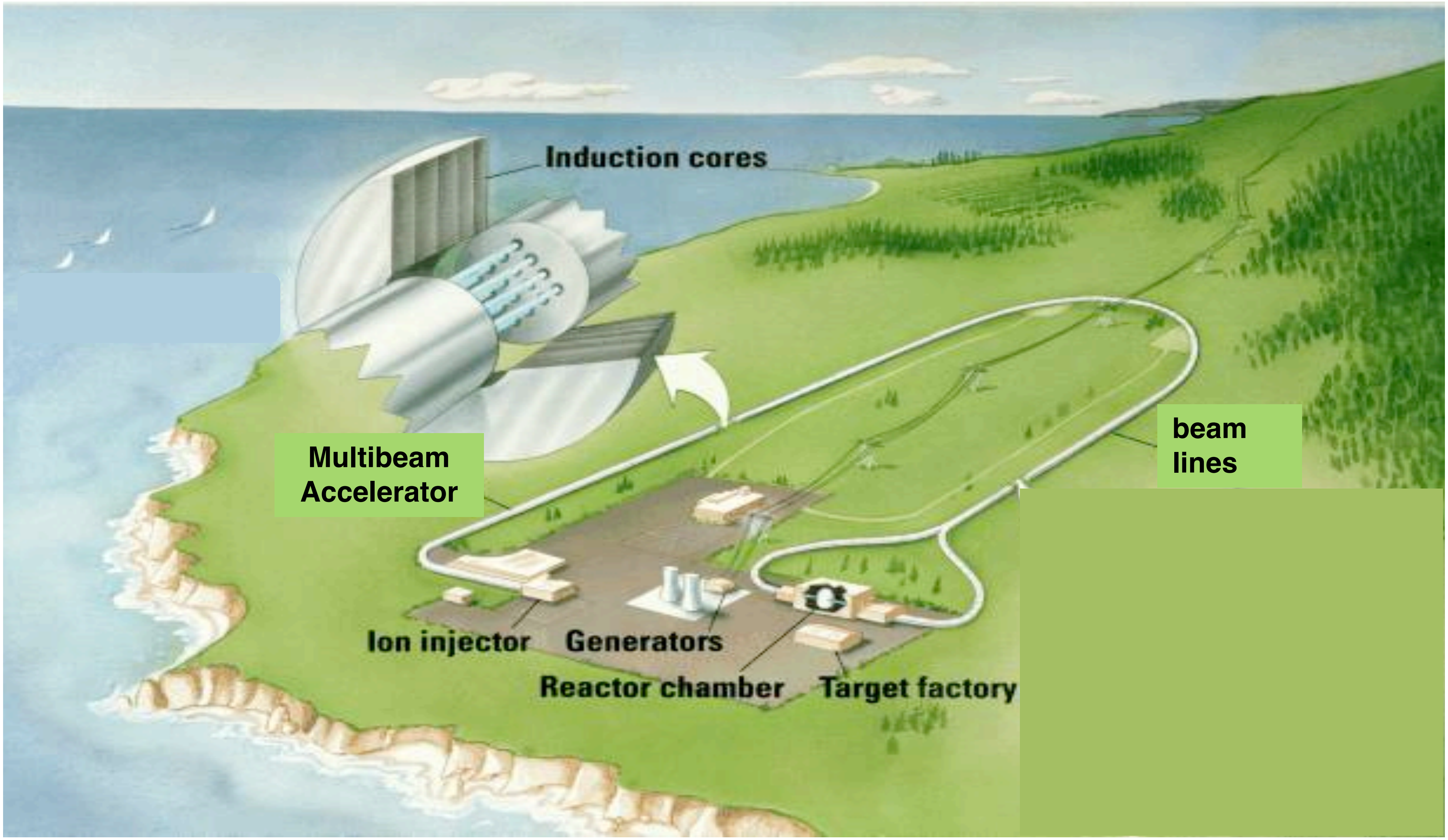
The HIF program's goal is an environmentally attractive and economical IFE power plant



Heavy ion accelerators are a good choice for an Inertial Fusion Energy driver

High Energy Physics accelerators already have:

- Long life
- High pulse repetition rates
- High electrical efficiency (~ 30%)
- Present systems comparable to requirements in:
  - complexity
  - cost
  - ion energy

If accelerators are so mature a technology, why is building a fusion driver challenging?

New physics regime for accelerators

Target Requirements:

500 Terawatts (but maybe less …)

1- 10 GeV

$\Downarrow$

~ 10^{16} ions

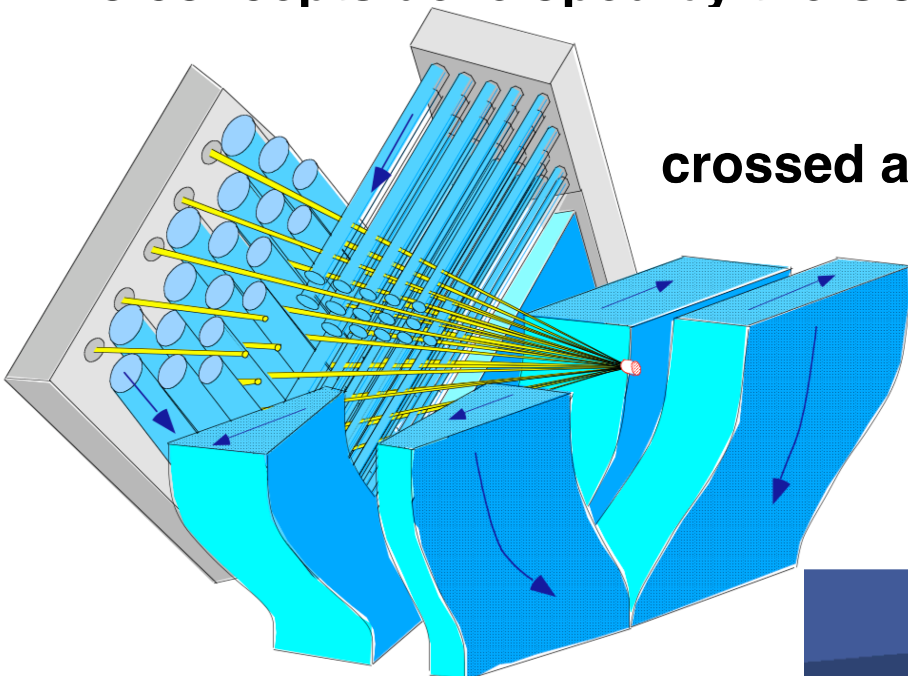
~ 100 beams

a million times more ions than in conventional machines

Beam particles interact -- this dominates the physics.

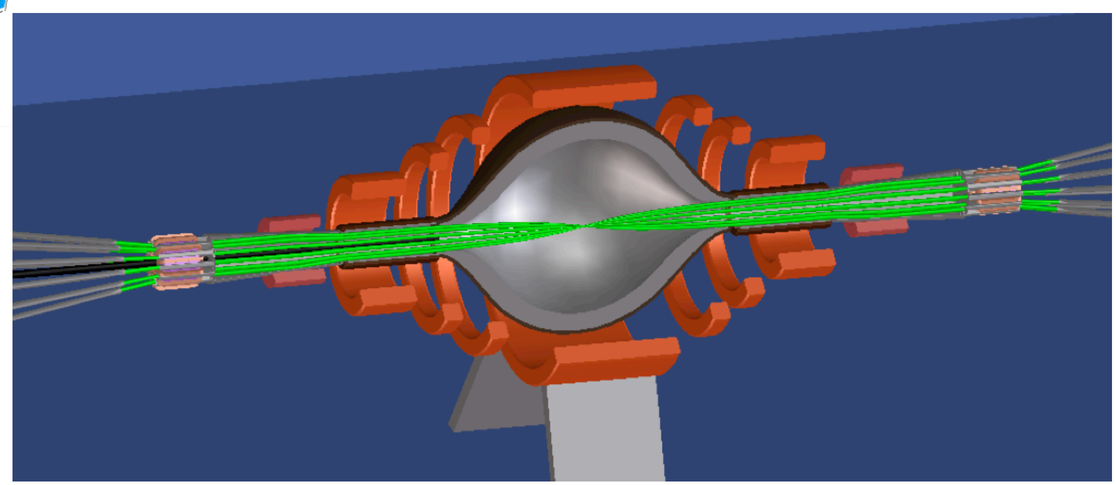
In most HIF concepts, the first wall is protected by neutronically-thick liquid, commonly FLiBe, a molten salt

Two concepts developed by the UC Berkeley group and its collaborators:

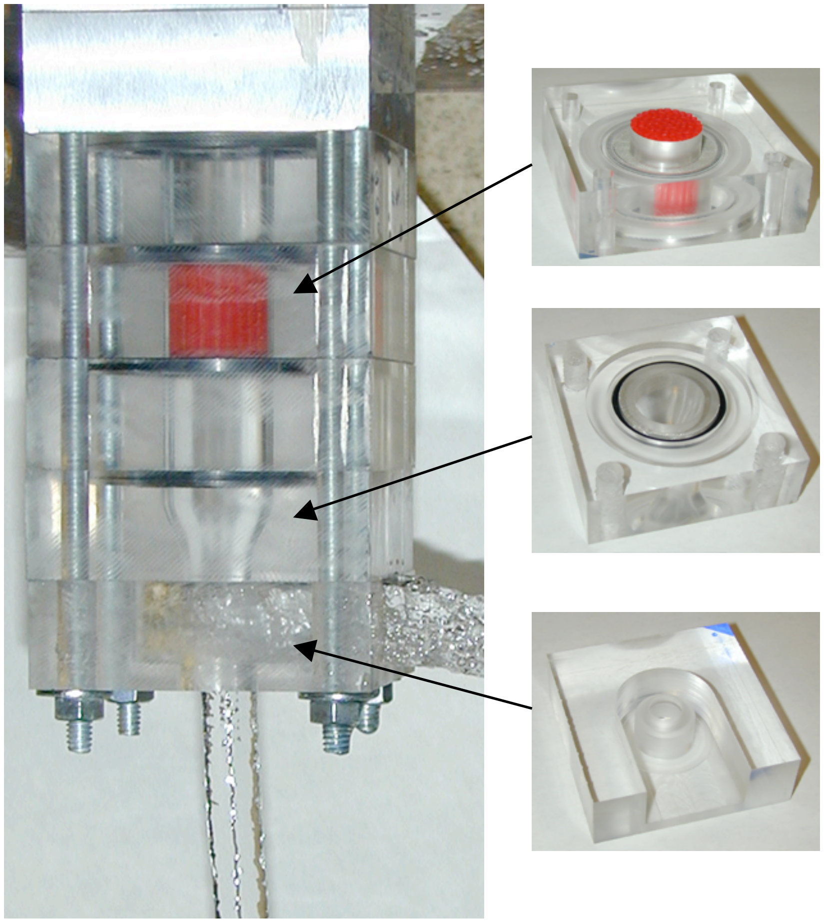


crossed and oscillating jets

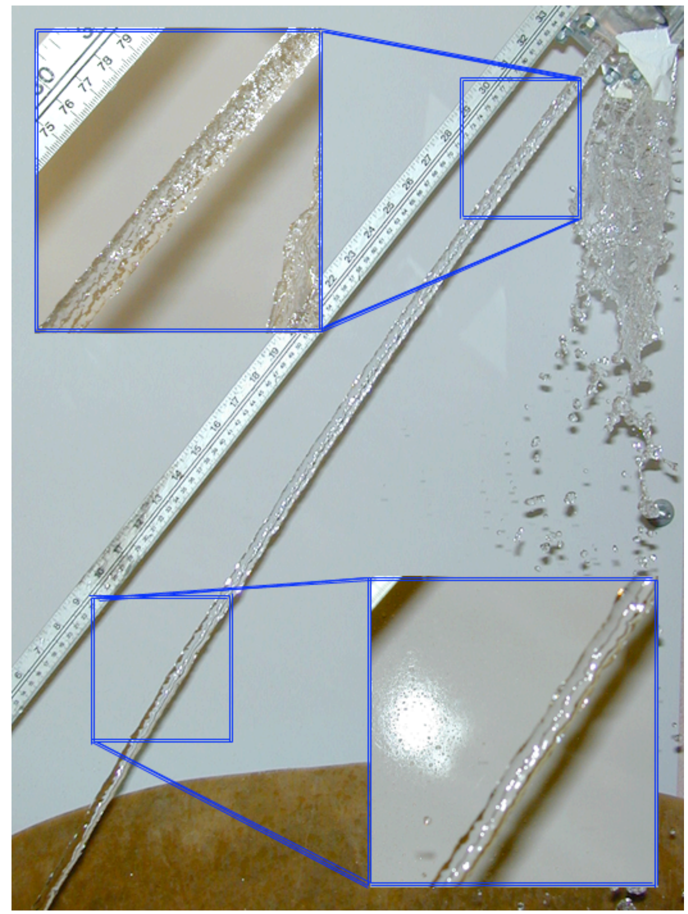
vortex flow



Experiments show cylindrical jets can be sufficiently smooth for beam-line protection

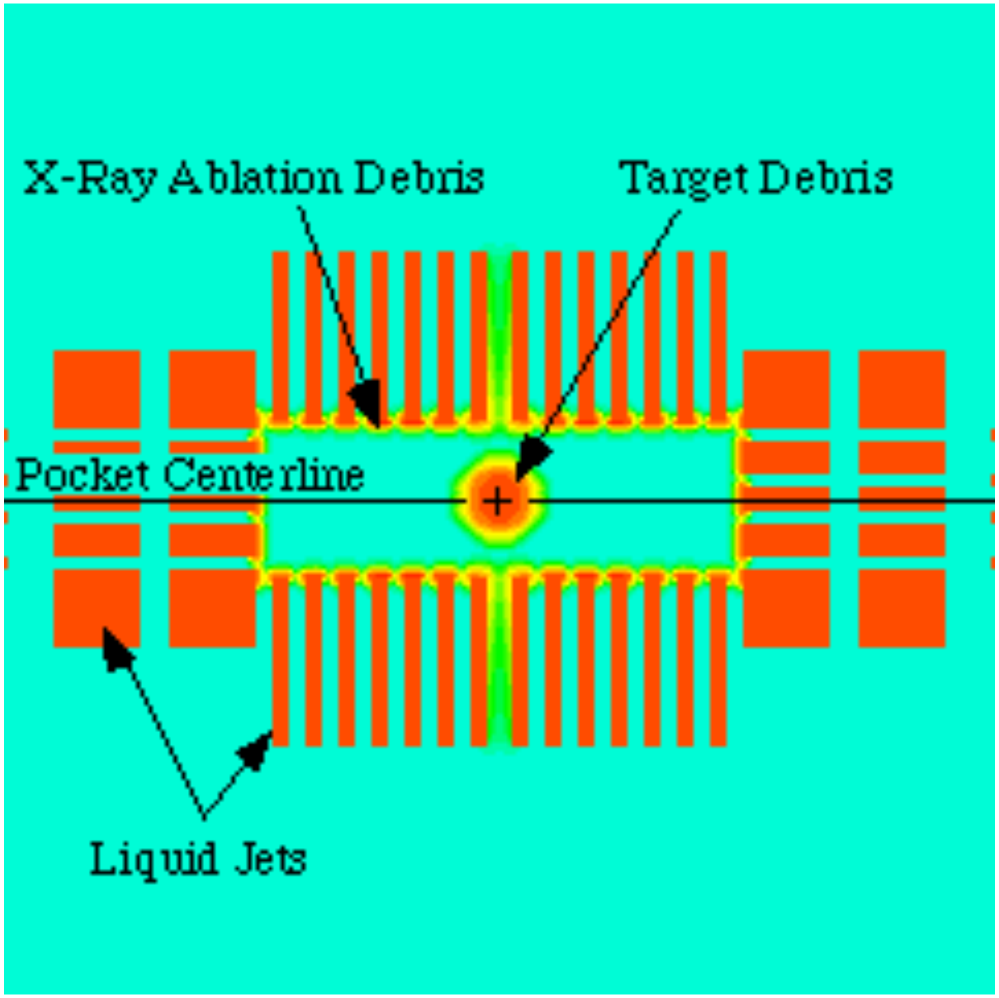


First UCB cylindrical jet experiment
7/13/2000



d_j = 1.3 cm Re = 70,000
v_j = 4.9 m/s

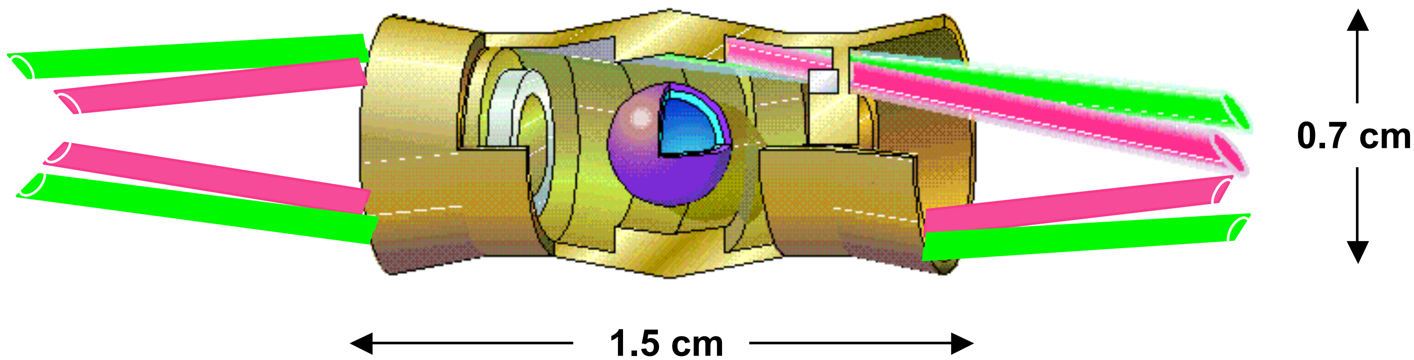
Chamber dynamics are simulated using the Tsunami code



Heavy Ion Fusion has traditionally assumed that targets will use "Indirect Drive" (NIF baseline)

Ion Beams ⇒ *x-rays*

X-rays symmetrize in hohlraum

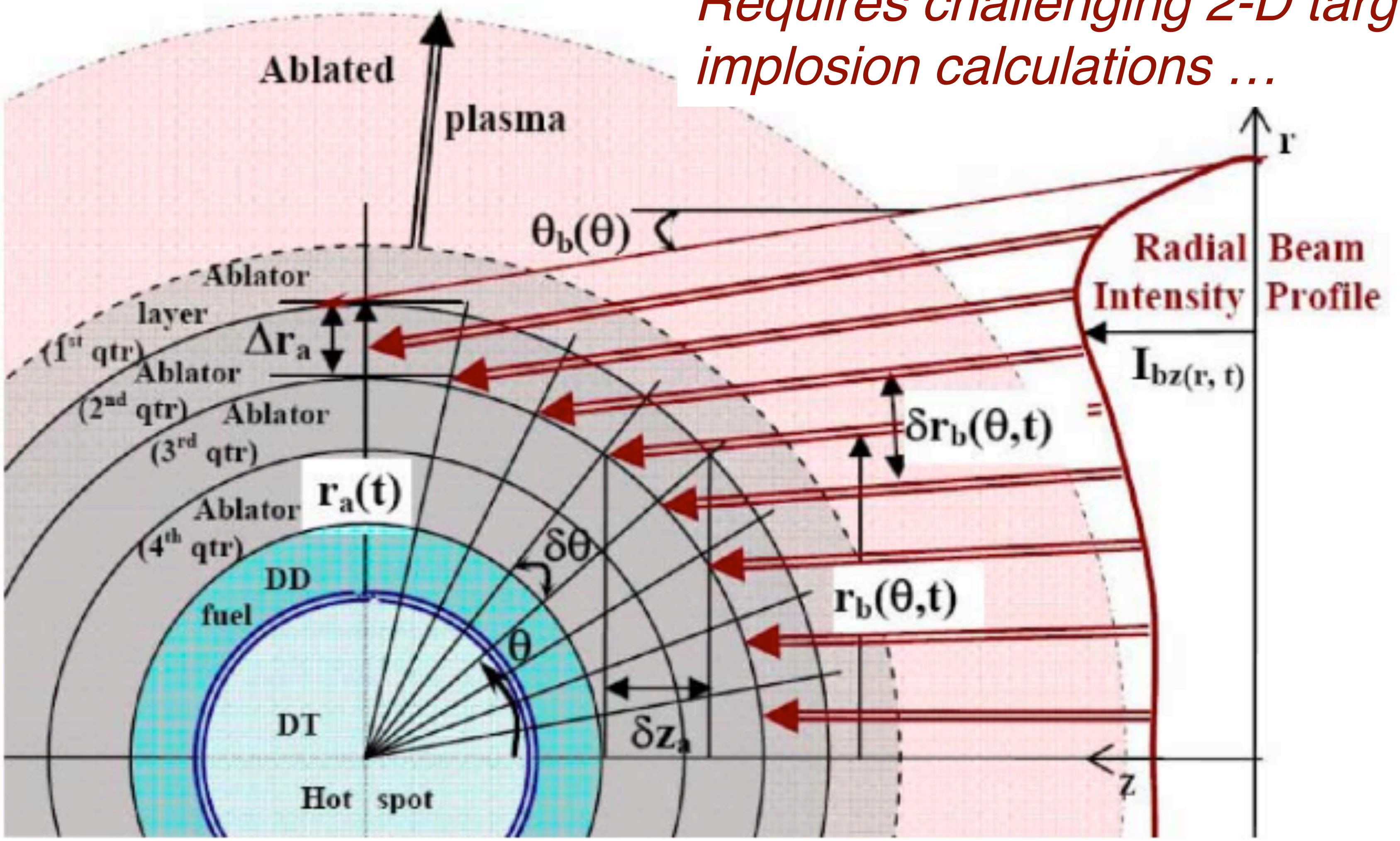


Requires ***~ 500 Terawatts (!!)*** **(3 - 7 MJ in ~ 10 ns)**

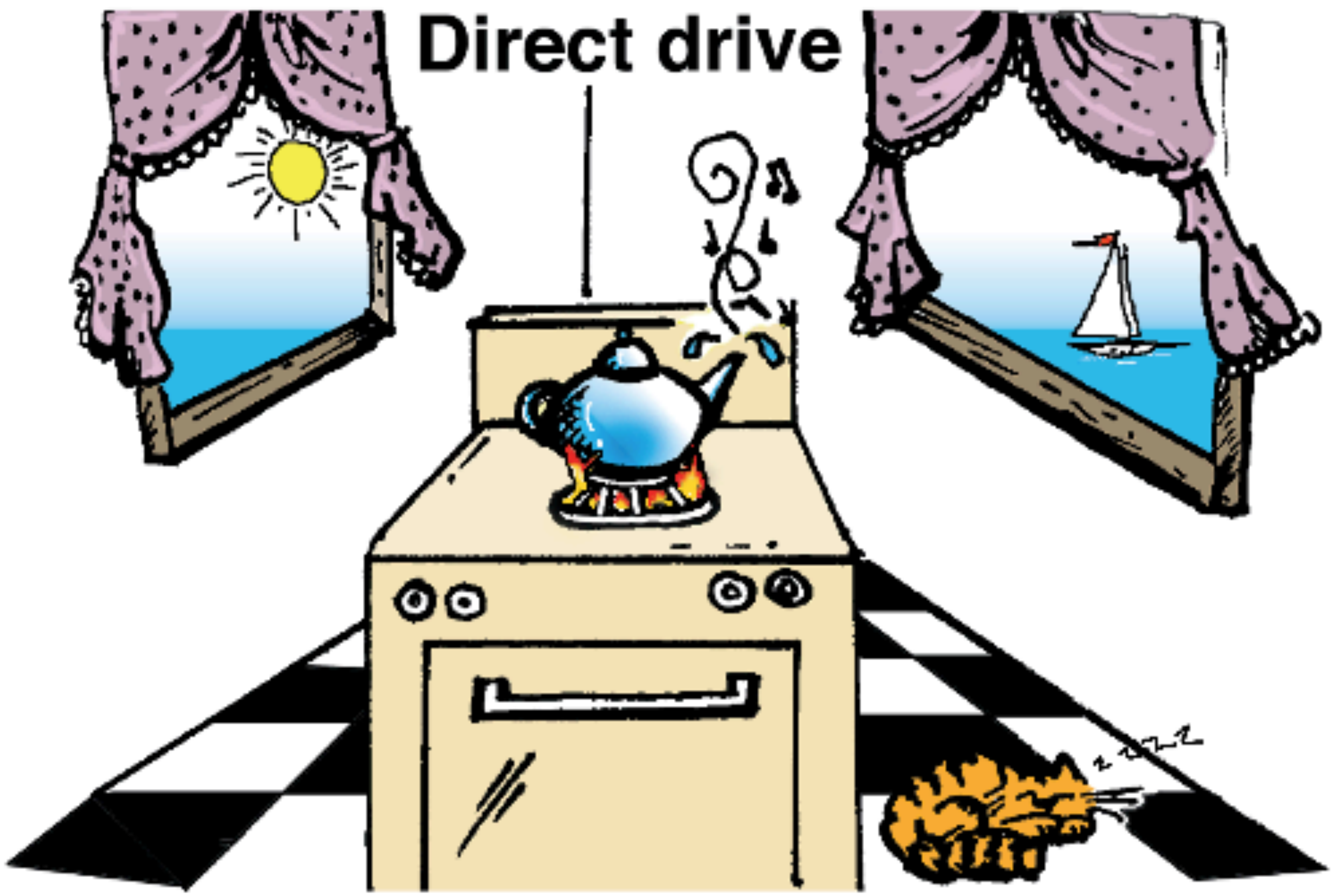
Ion Range⇒ ***1- 10 GeV*** **(about 1/3 the speed of light)**

New target ideas include ion direct drive, and even "polar direct drive"

Requires challenging 2-D target implosion calculations …

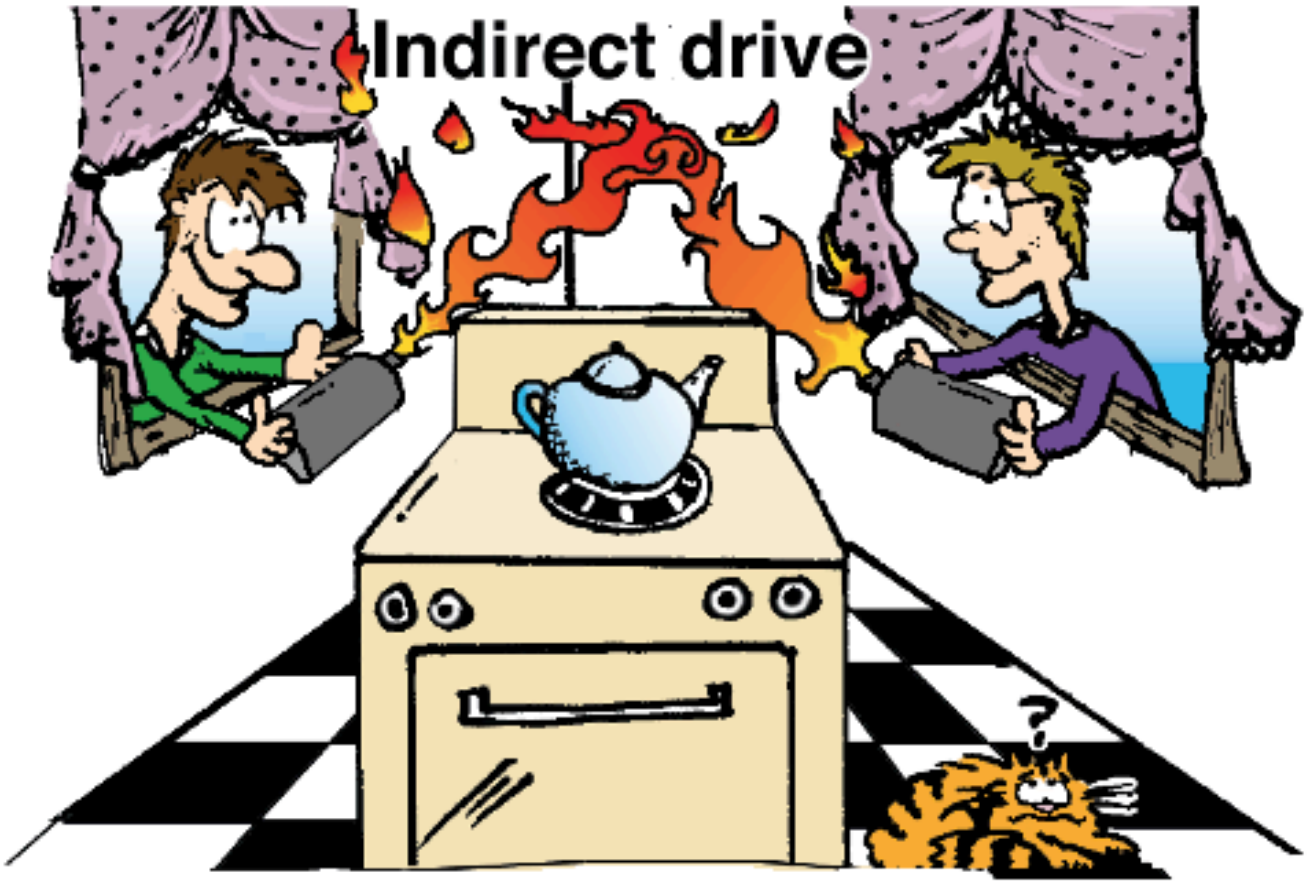


Direct drive isn't entirely a new idea (for electrons, ions, or teapots)



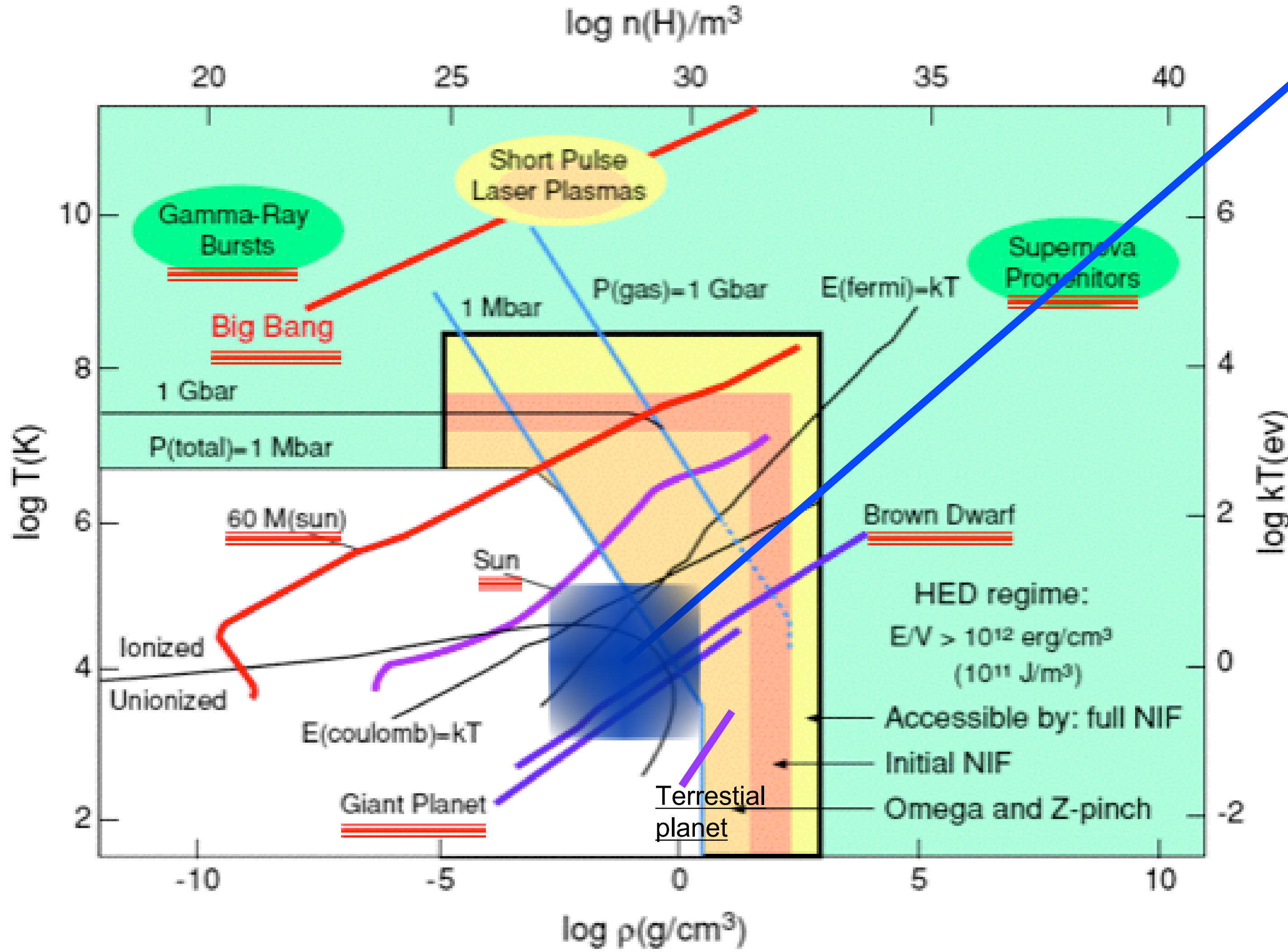
(R. L. McCrory, invited review, Meeting of the APS Division of Plasma Physics, 1981)

Indirect drive




"Guess we need a bigger kitchen and better flame throwers!"

HIFS-VNL's near-term mission: exploring the novel properties of matter in the "Warm Dense Matter" (WDM) regime



The regime in ρ - T space that is accessible by **beam driven experiments** lies square in the interiors of gas planets and low mass stars

Figure adapted from "Frontiers in HEDP: the X-Games of Contemporary Science:"

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Plasmas and beams consist of a large number of interacting charged particles; a variety of models are used

– Particle motion mathematically described by
  - Lagrangian approach: evolution of discrete markers
  - Eulerian approach: evolution of an incompressible fluid
    in phase-space:
    - with collisions: Boltzmann/Fokker-Planck eq.
    - no collisions: Vlasov eq.

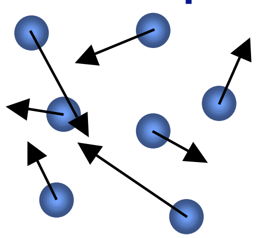
    in real space: fluid/MHD eq.

– Interactions mathematically described by
  - Lagrangian approach: sum over all markers
    instantaneous: Green functions
    with retardation: retarded Green functions
  - Eulerian approach: fields
    instantaneous: Poisson, “Darwin” (magneto-inductive)
    with retardation and EM waves: Maxwell

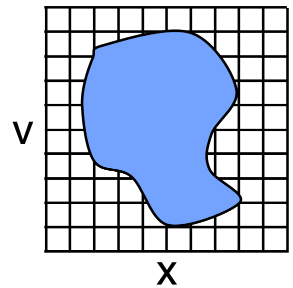
Modeling involves choices

- In summary, the modeling of a plasma implies the modeling of:

a collection of particles **fluid cells in phase-space** **fluid cells in configuration space**



or



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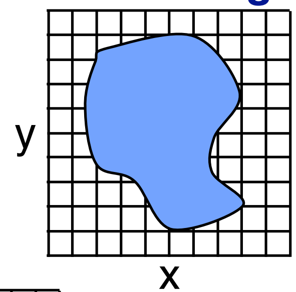
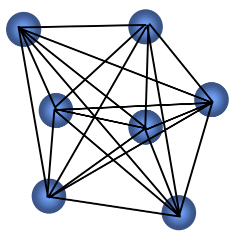
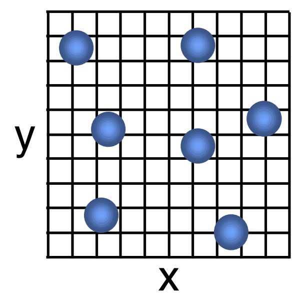


interacting either:

directly



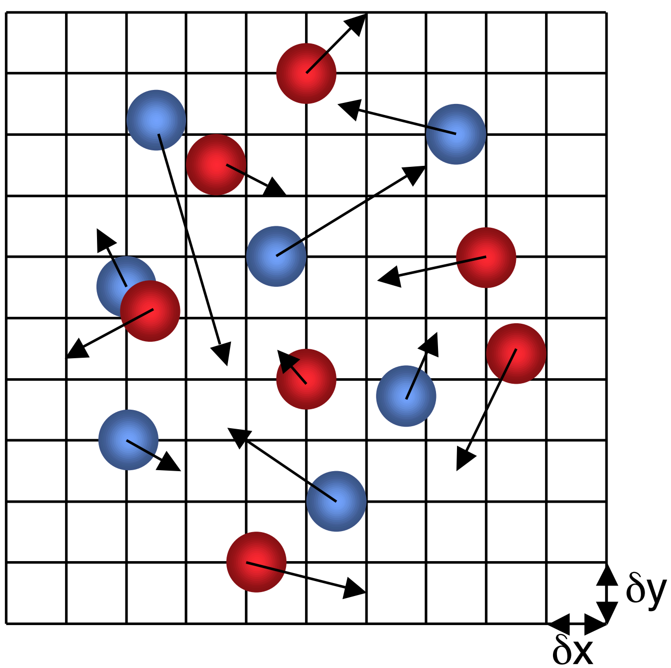
or through a field

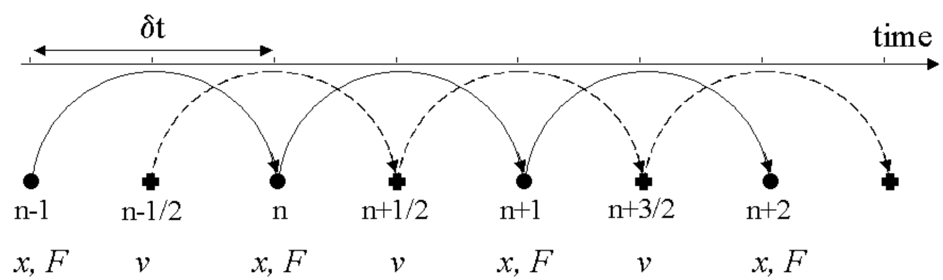


- The numerical integration leads to more choices
  - Partial differential equations: finite-differences/volumes/elements, Monte-Carlo, semi-Lagrangian, …
  - Time integration: explicit/implicit, “symplectic,” …
  - Direct interaction: direct summation, multipole expansion (tree-codes), …
  - …

We use (primarily) the Particle-In-Cell (PIC) method

– We use macroparticles (1 macroparticle = many real particles)
– We compute the force (fields) on a grid (electrostatic or EM)
– We advance particle and fields by finite time steps





Simulation loop connects particle advance & field solution (here, a simple electrostatic example)

using particle positions $\mathbf{x}_i^n$, deposit charges q_i onto grid (a weighted sum) to obtain charge density ρ^n at grid points

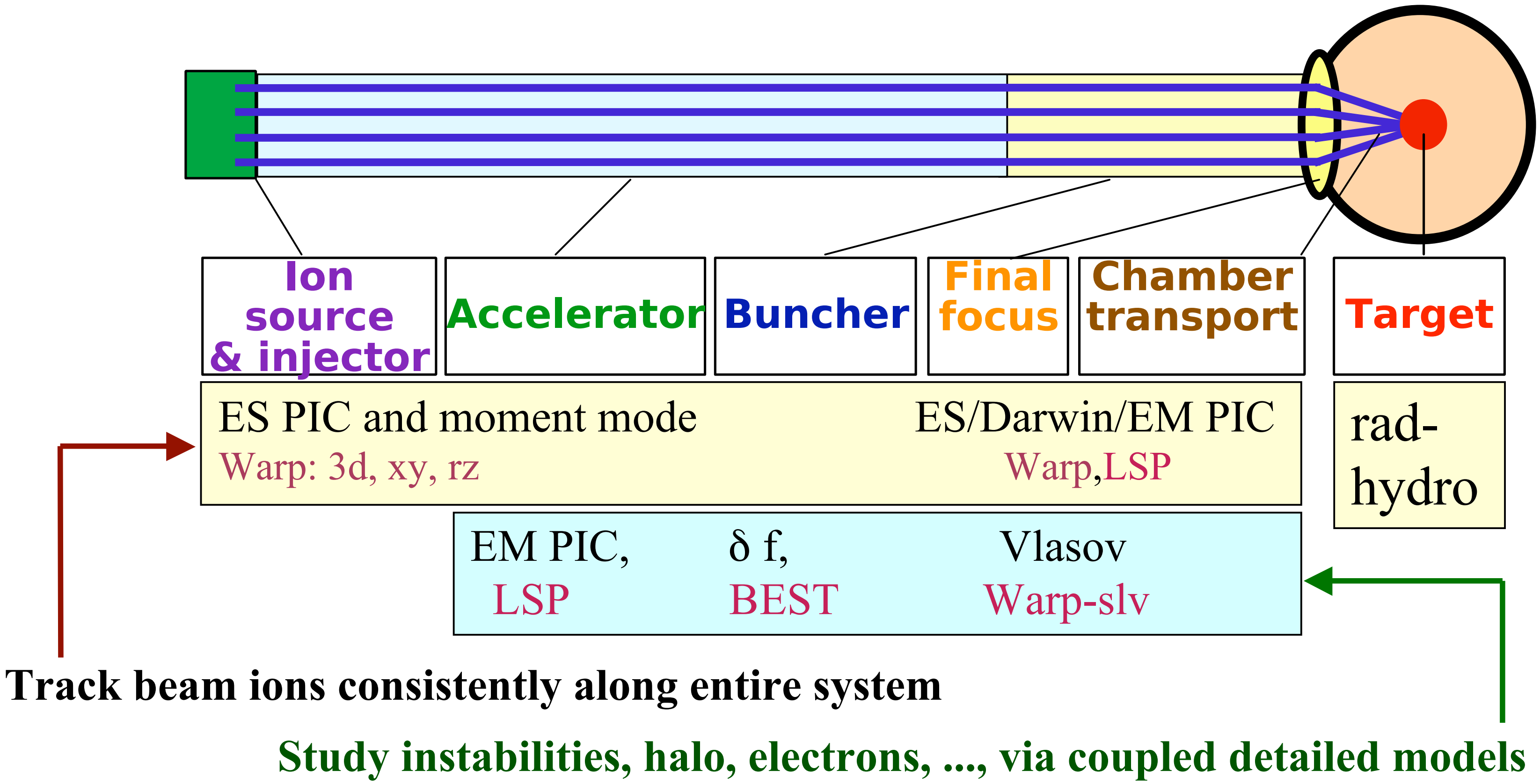
solve for field on grid
$$\nabla \bullet \mathbf{E}^n = \rho^n/\varepsilon_0$$

Interpolate $\mathbf{E}^n$ from grid onto particle positions $\mathbf{x}_i^n$, to obtain localized field values $\mathbf{E}_i^n$

advance particles
$$\mathbf{v}_i^{n+1/2} = \mathbf{v}_i^{n-1/2} + \Delta t\, q_i \mathbf{E}_i^n/m_i$$
$$\mathbf{x}_i^{n+1} = \mathbf{x}_i^n + \Delta t\, \mathbf{v}_i^{n+1/2}$$

(increment step counter n)

HIF systems are broken into pieces that can be studied separately



- We compute on Mac's, pc's, linux boxes and clusters, parallel supercomputers
- Even on supercomputers, simulation of all the real particles is generally impractical
  => we have to make approximations!

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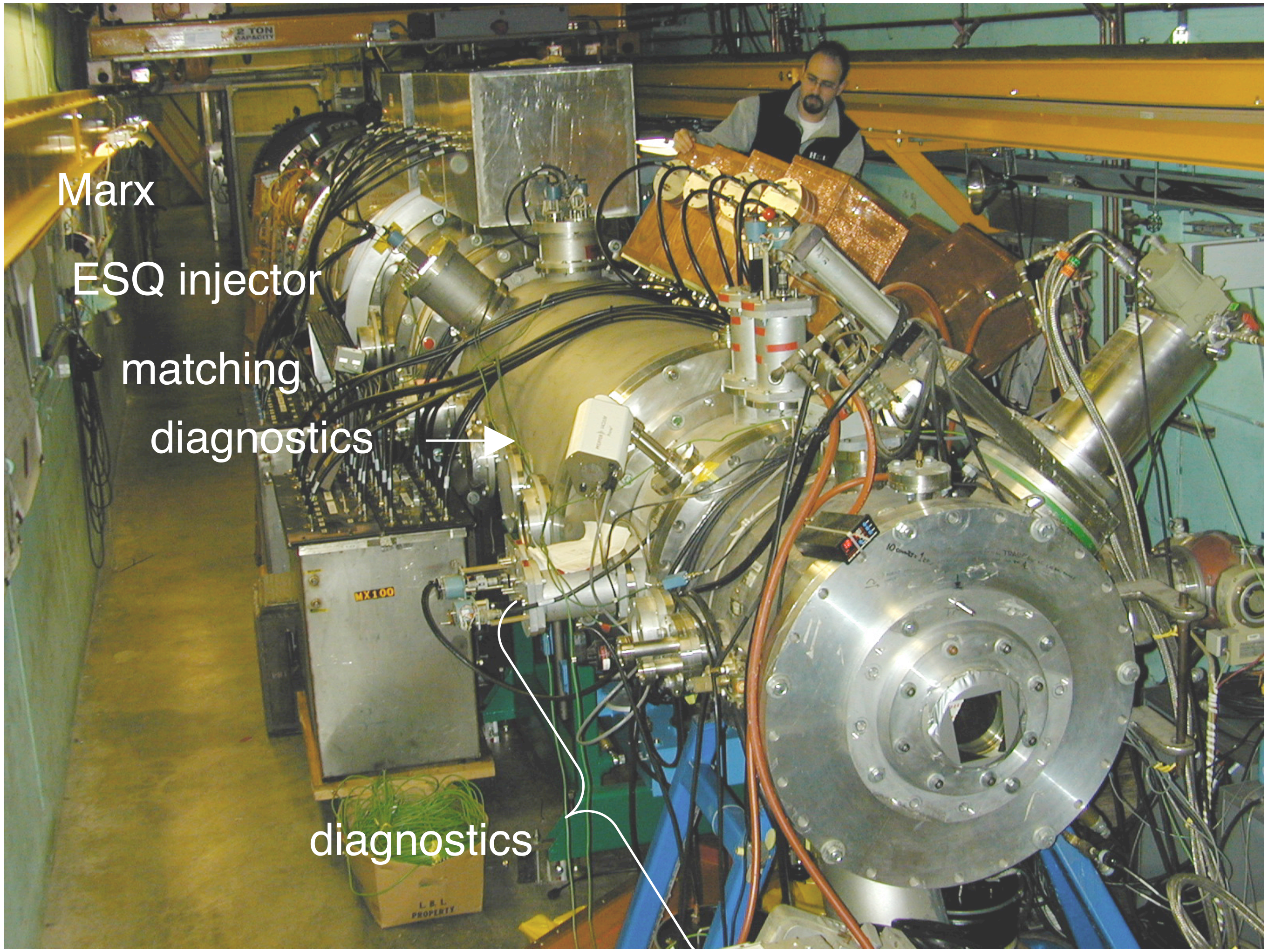
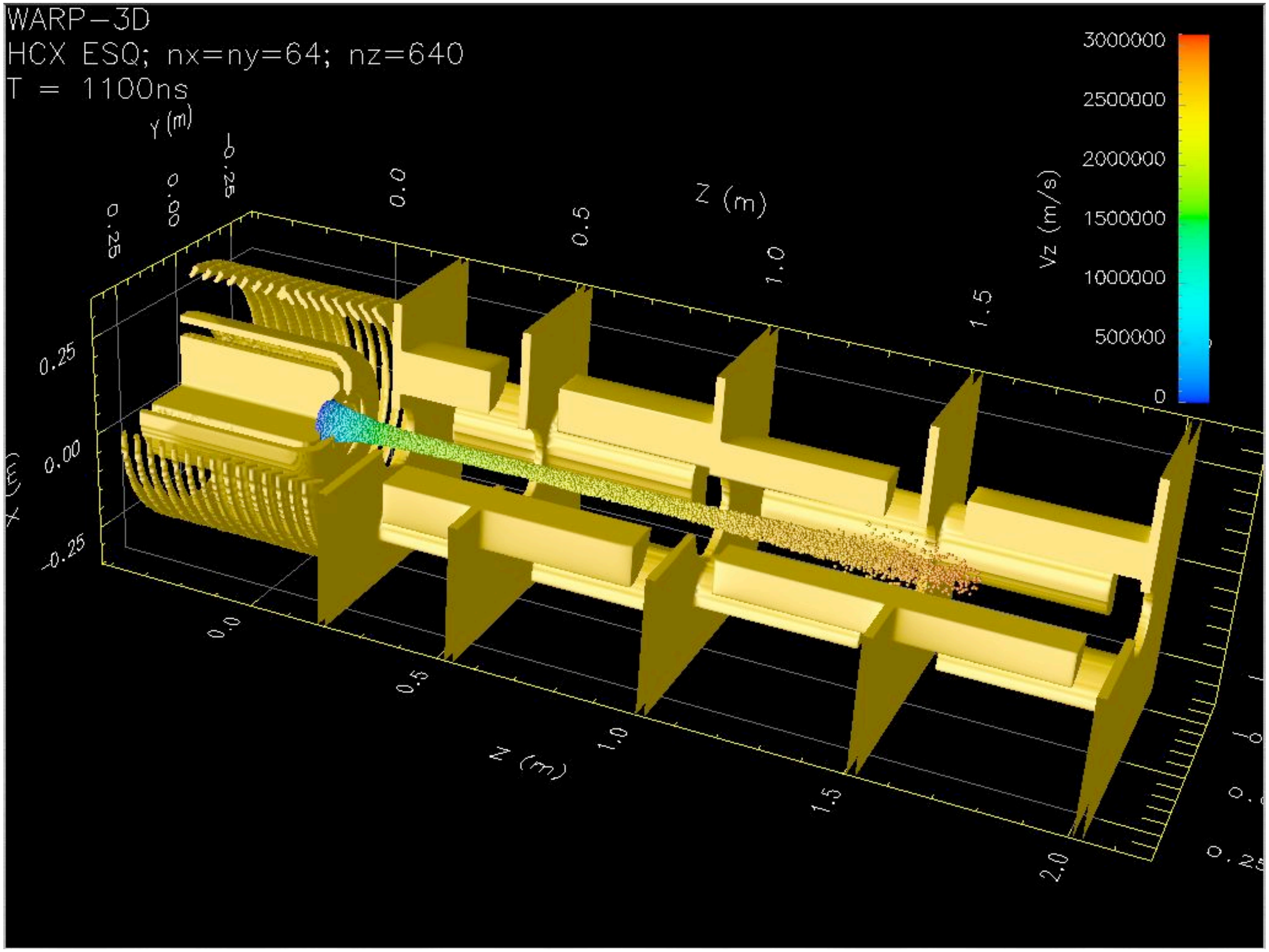
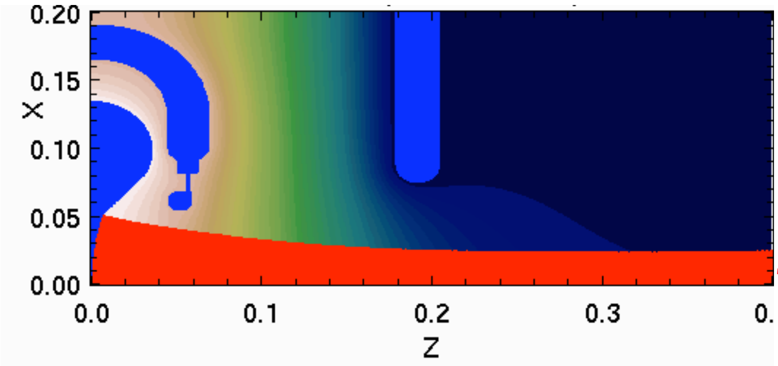
High Current Experiment (HCX) at LBNL offers 1-2 MV ion beams

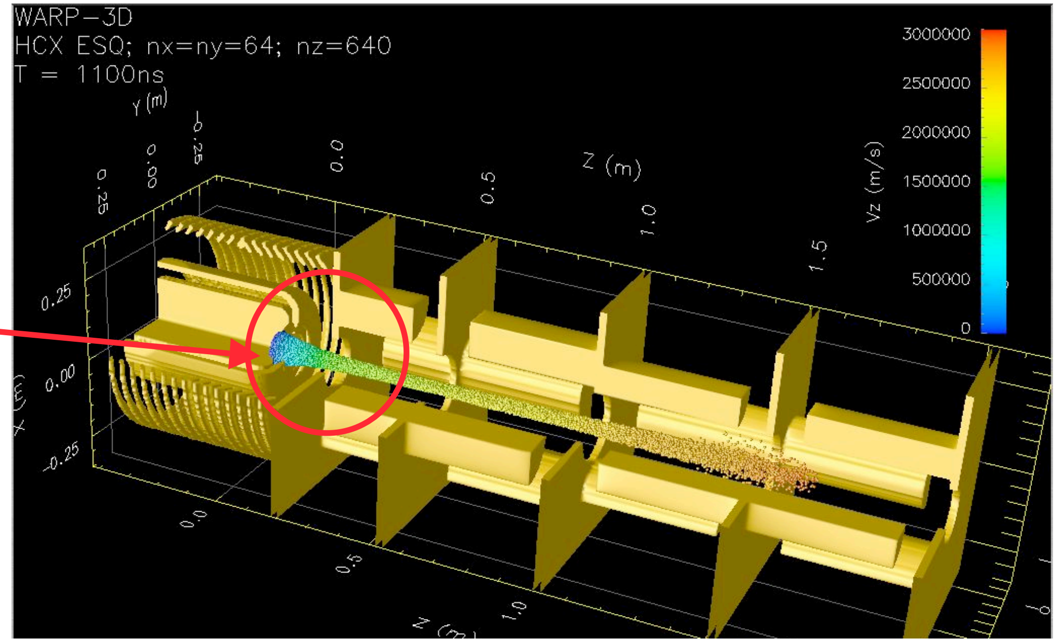


3-D WARP simulation of HCX injector

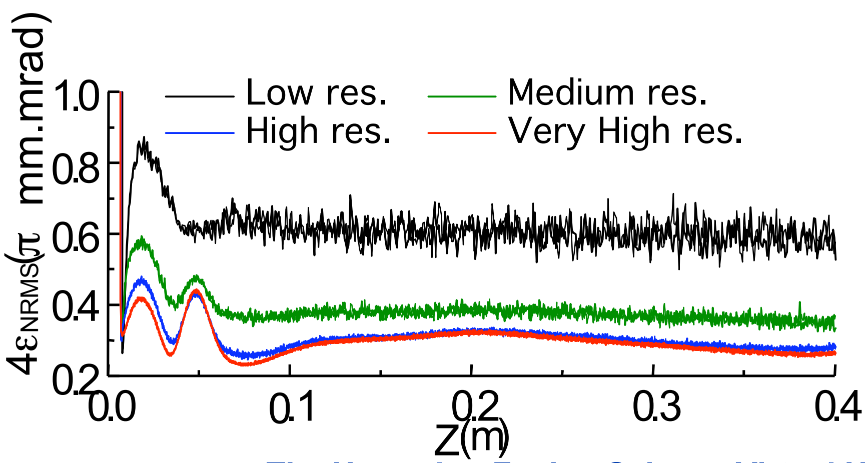


Modeling of source is critical; collisionless beams have a "long memory"





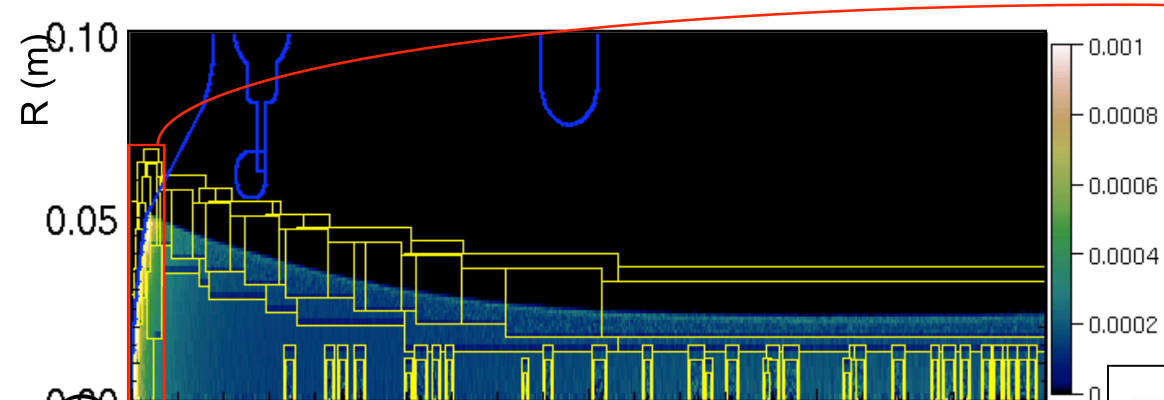
WARP-RZ (axi-symmetric) simulations of source show that a fairly high resolution is needed to reach convergence

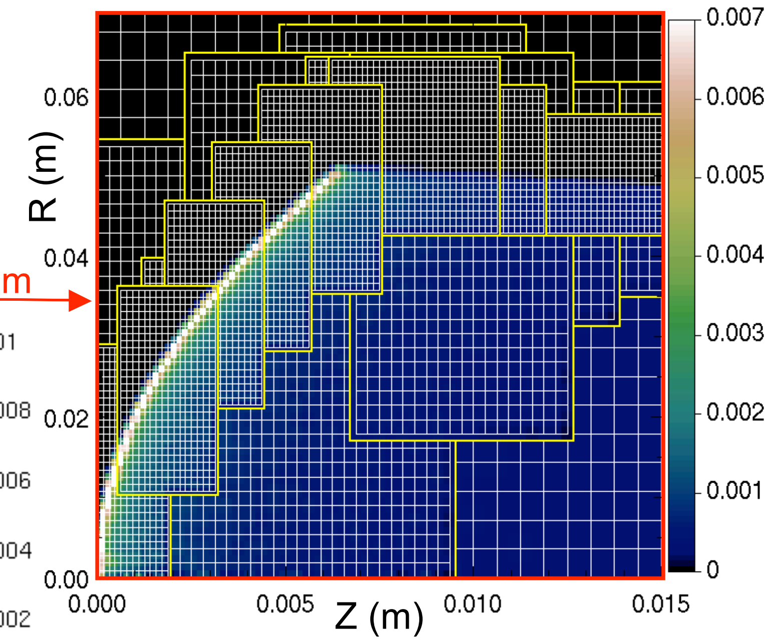


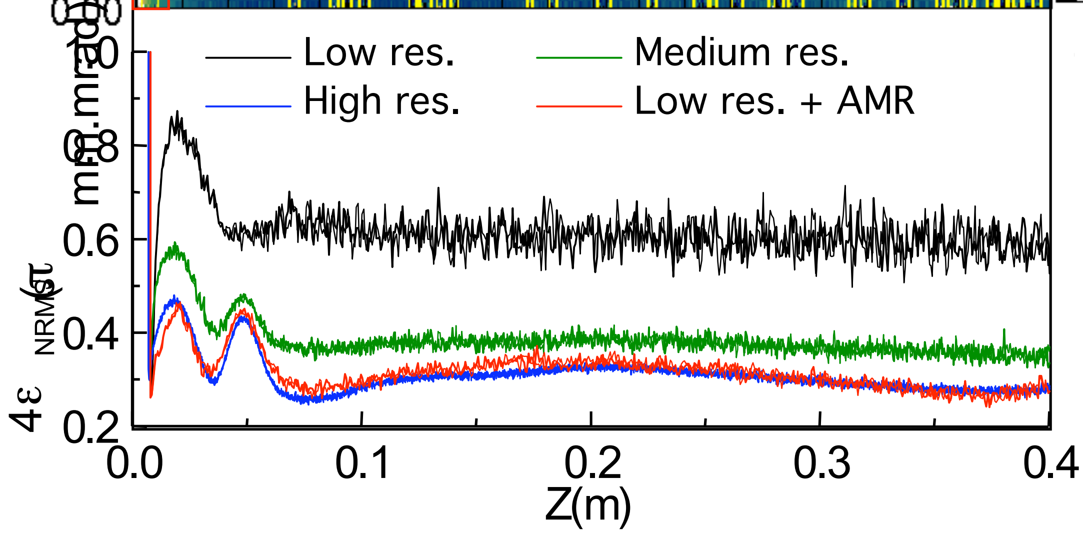
Run	Grid size	Nb particles
Low res.	56x640	~1M
Medium res.	112x1280	~4M
High res.	224x2560	~16M
Very High res.	448x5120	~64M

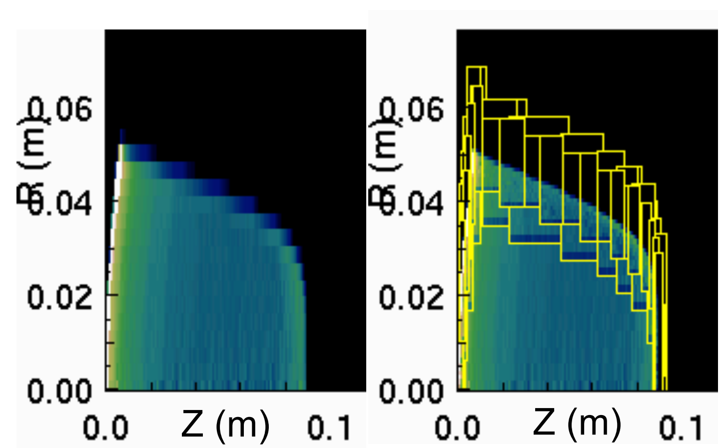
We have merged PIC+AMR: speedup ~10.5

Run	Grid size	Nb particles
Low res.	56x640	~1M
Medium res.	112x1280	~4M
High res.	224x2560	~16M
Low res. + AMR	56x640	~1M





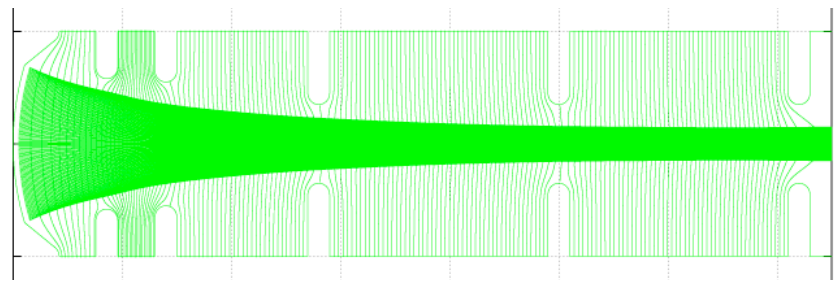




Refinement of gradients: emitting area, beam edge and front.

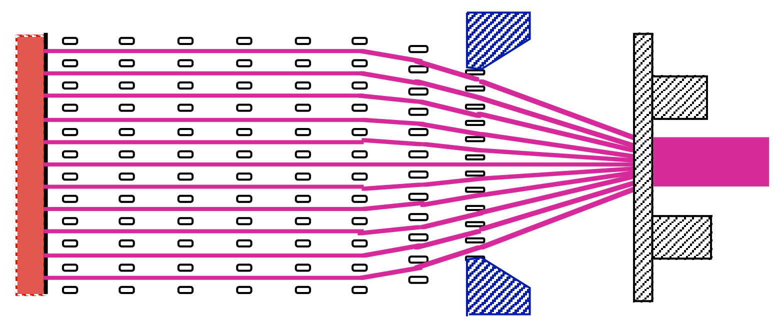
We have explored a compact ion source approach

- Traditional: use a large diameter but low current density single-aperture ion source.



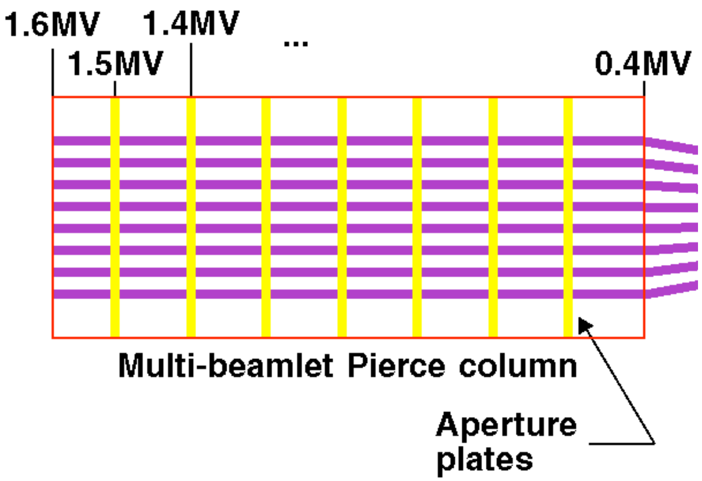
4 mA/cm^2

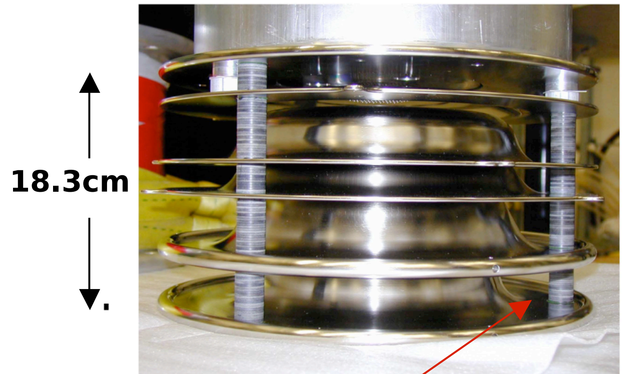
- New: extract hundreds of mm-scale high current density *beamlets*, from a multiple-aperture ion source.



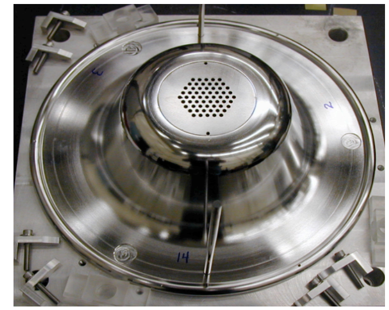
100 mA/cm^2/beamlet

Merging beamlet high gradient experiment: simulation challenging: large 3-D run on parallel supercomputer.

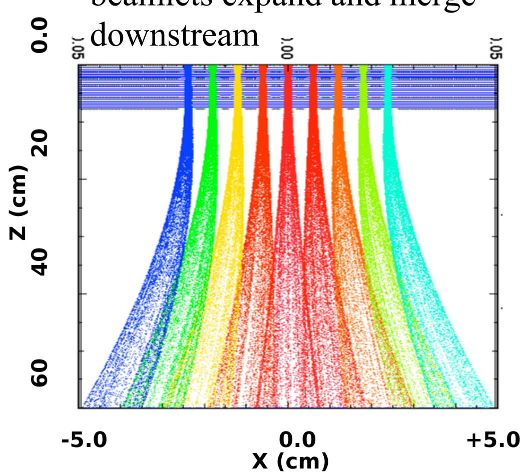




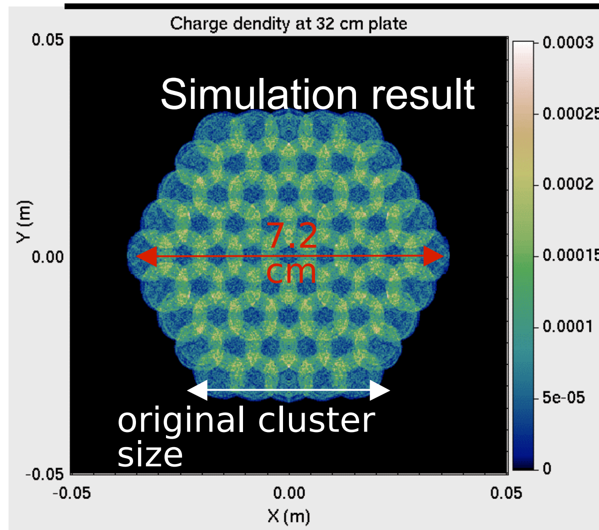
High Gradient Insulators
held 30 kV/cm

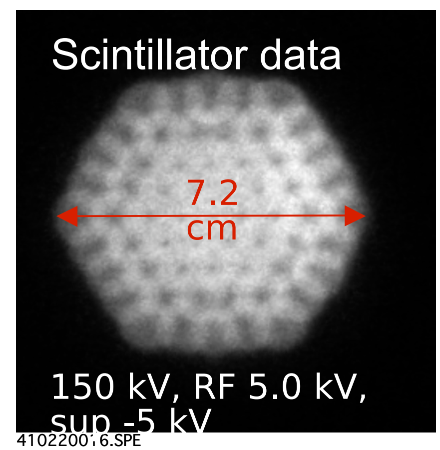


Warp 3D simulation of beamlets expand and merge downstream

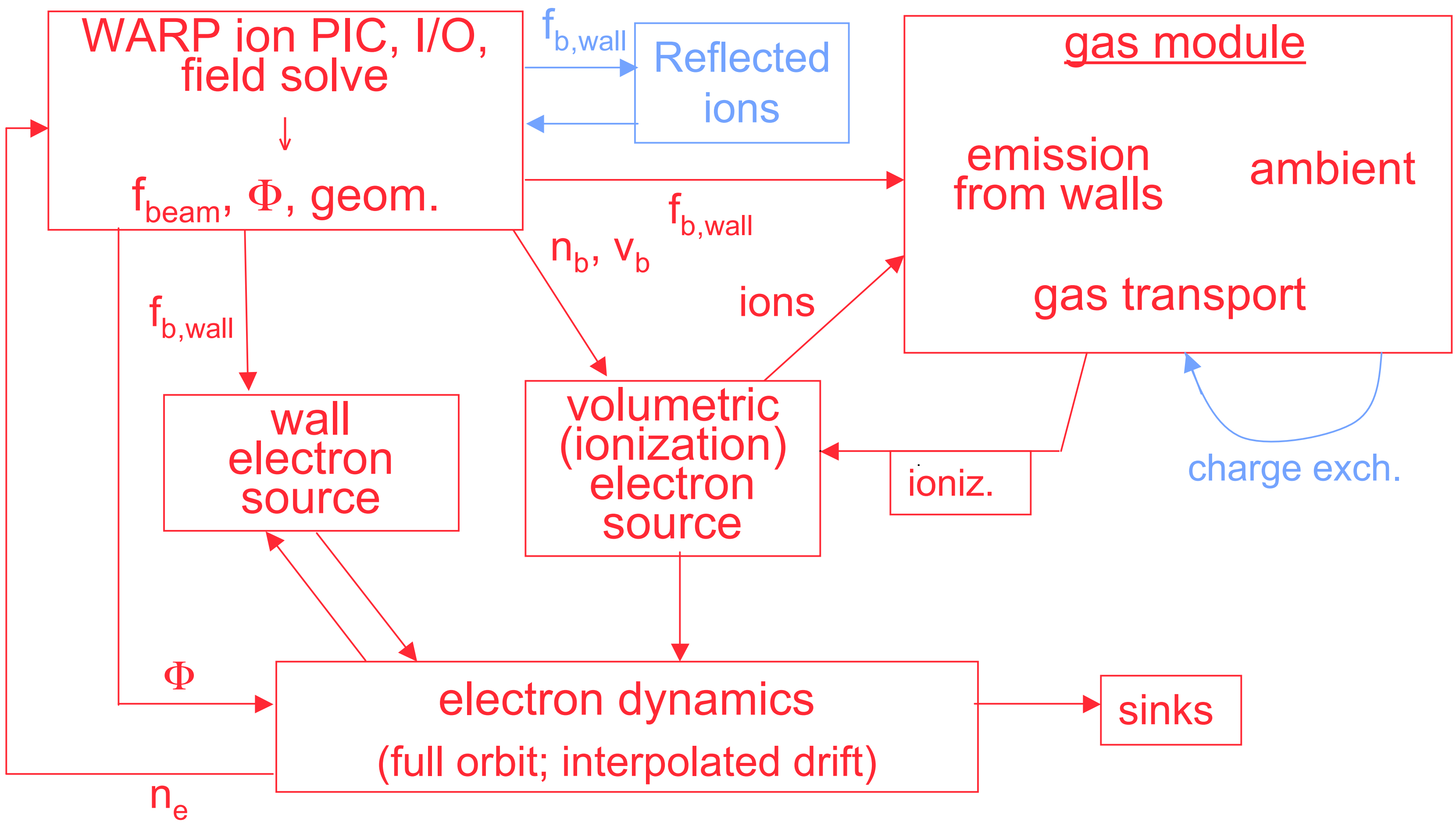


Z = 15 cm



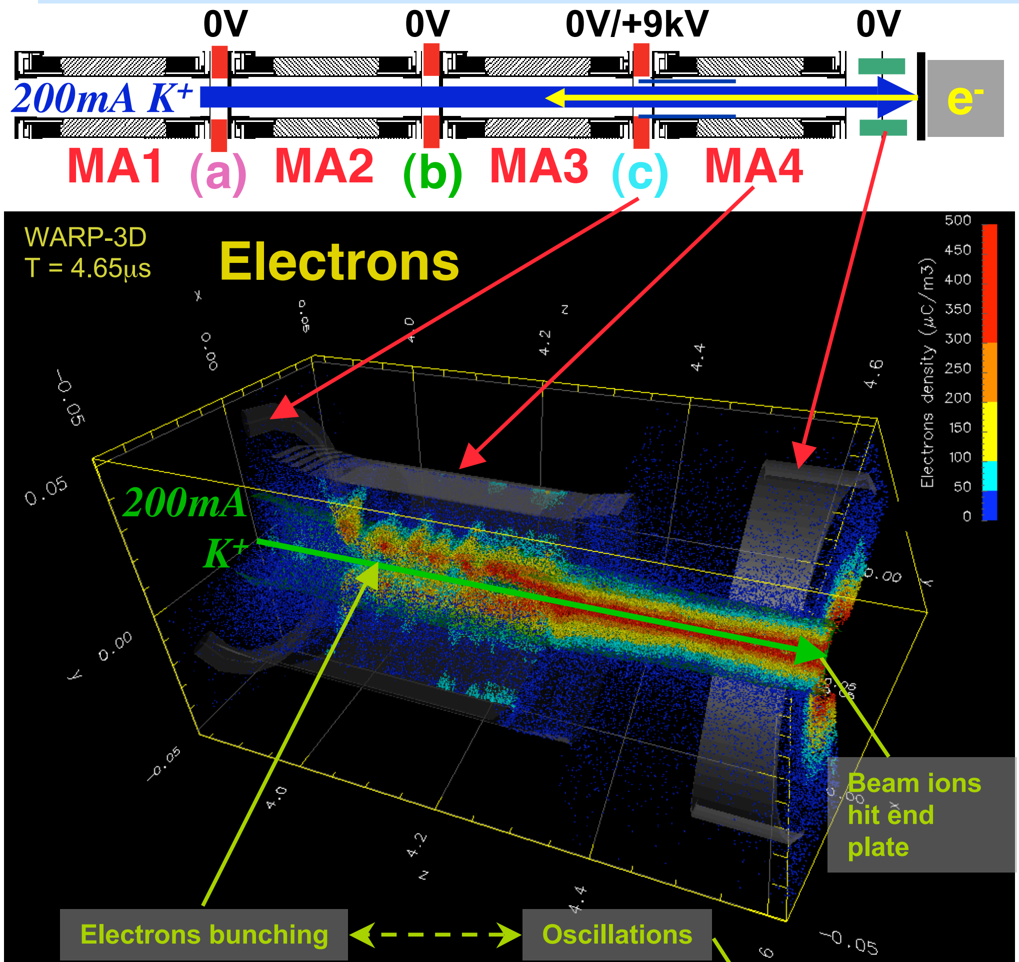


"Roadmap" for self-consistent modeling of beam with electron cloud & gas effects

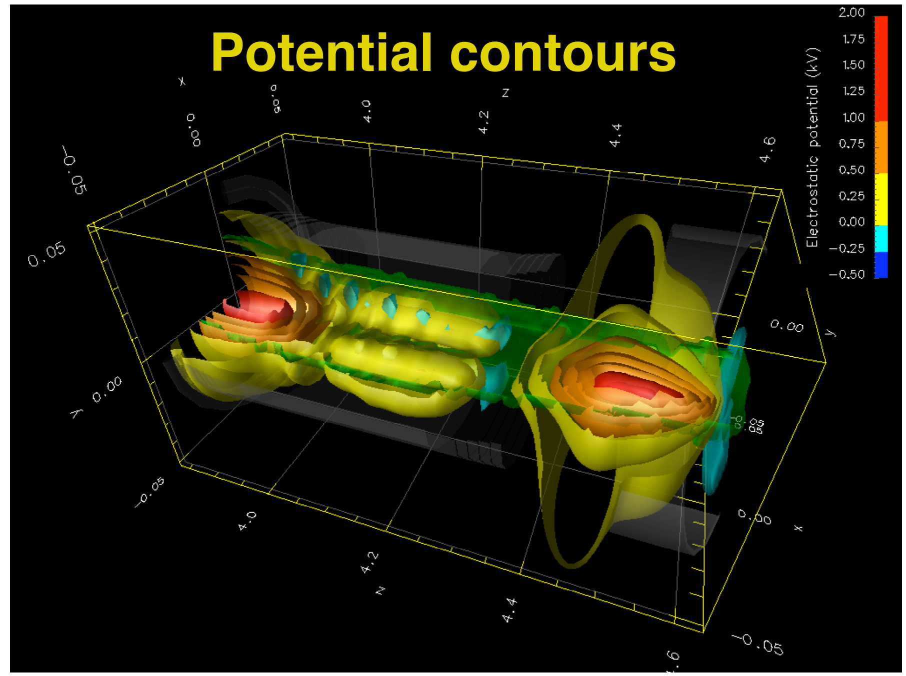


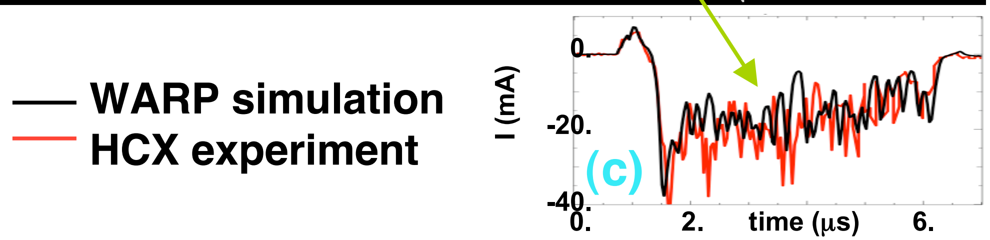
- Key: operational; partially implemented (5/6/05)

Beam hits end-plate in HCX to generate copious electrons; bunching observed in simulations and experiments



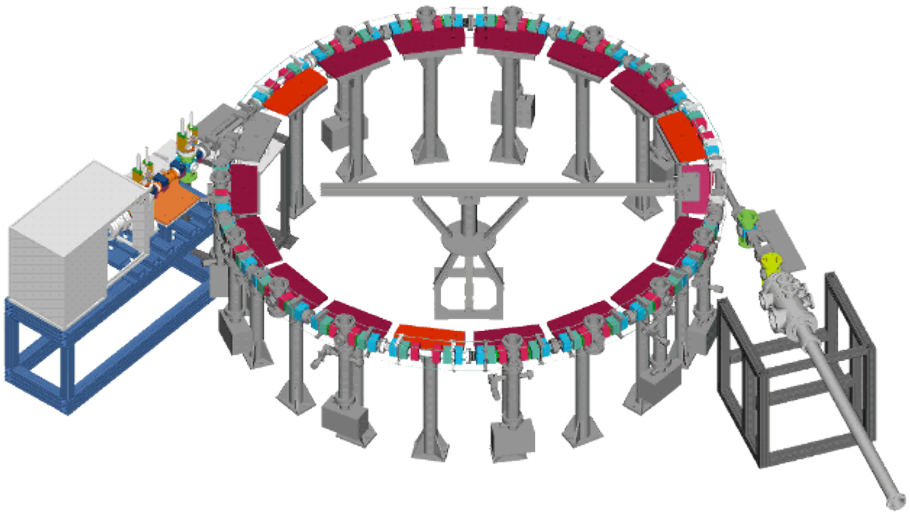
Wavelength of ~5 cm, growing from near center of 4th quad. magnet

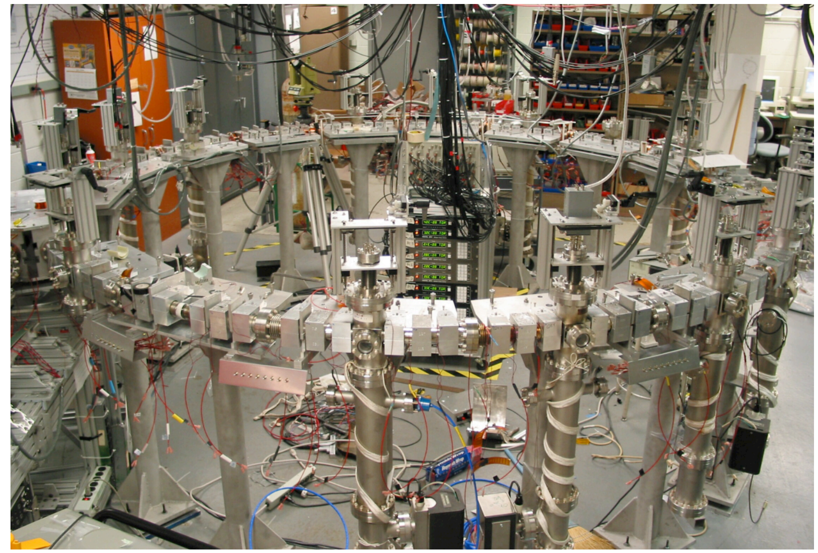


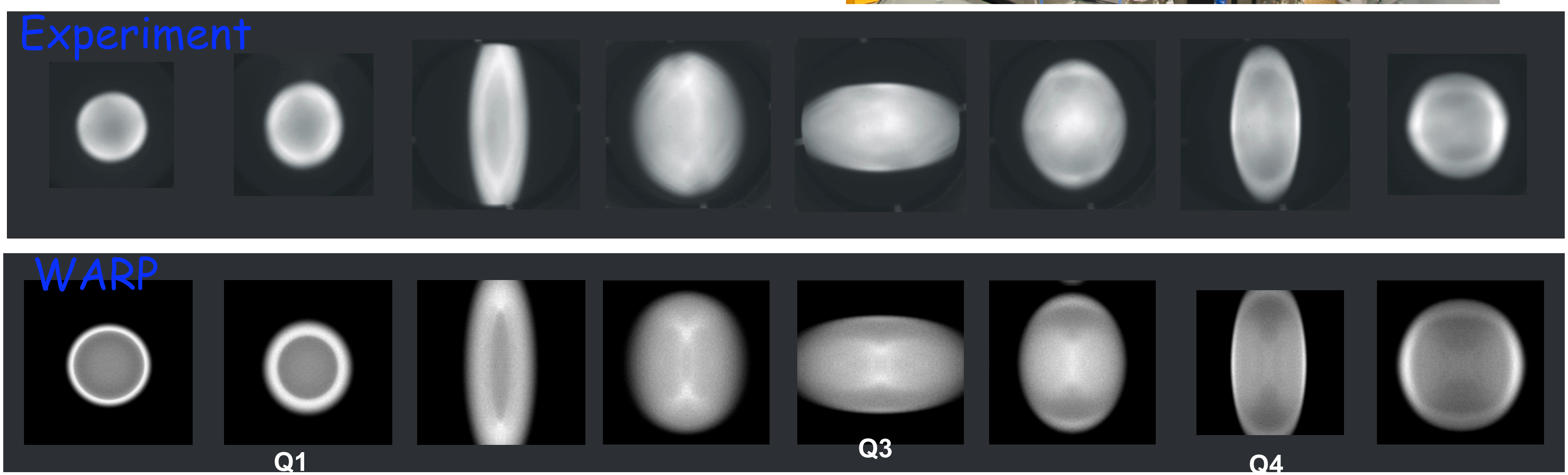


~6 MHz signal in clearing electrode (C)

WARP simulations support the University of Maryland Electron Ring experiments







The rings are due to edge lensing

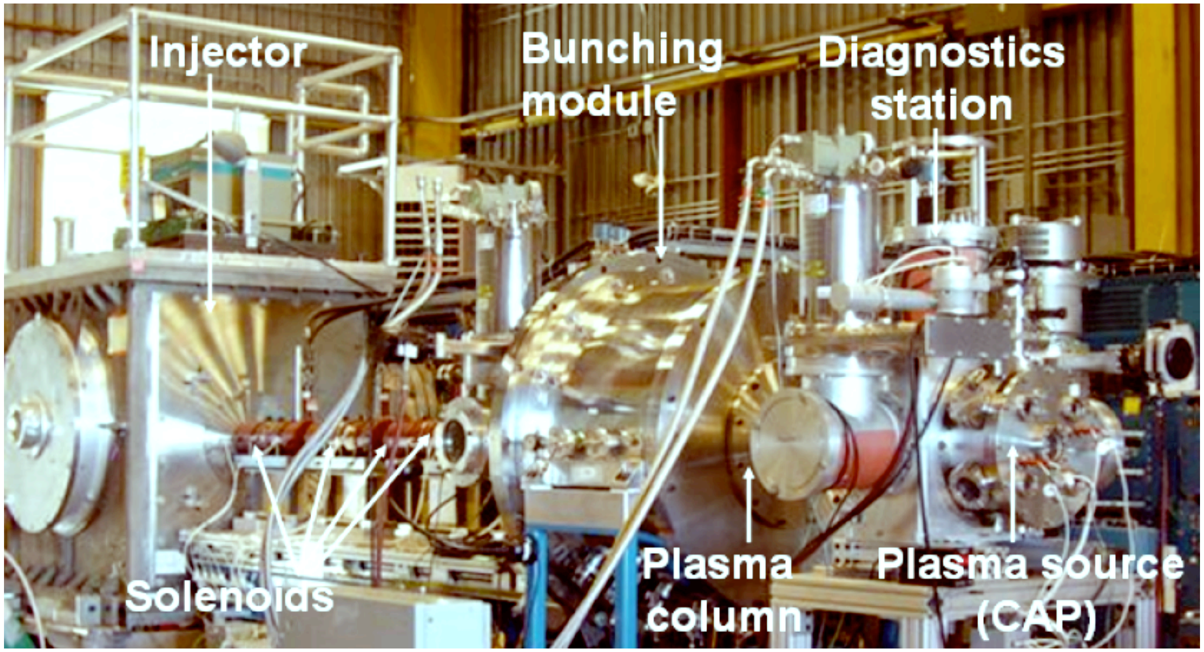
Talk Outline

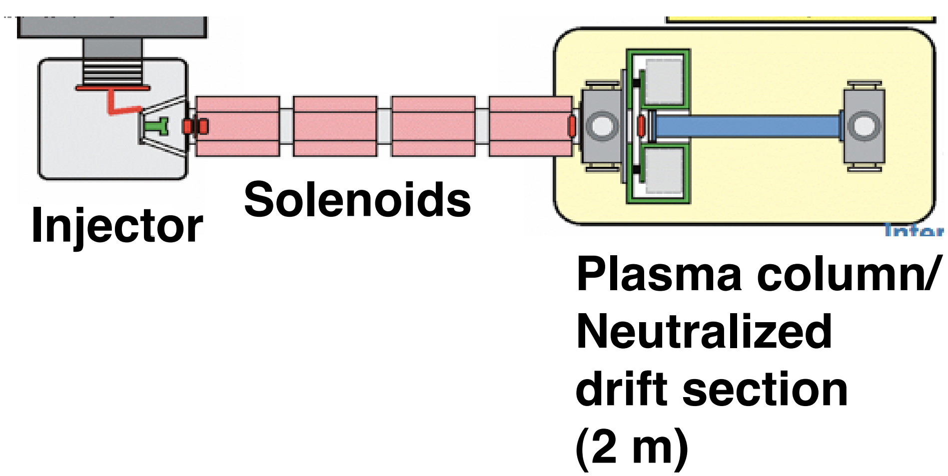
- Fusion
  - Introduction
  - The Heavy Ion Fusion program
- Modeling plasmas and beams - taxonomy of methods
- HIF experiments and simulations
  - Non-neutral beams in accelerators
  - Neutralized beams in plasmas
  - Targets
- The next step - NDCX-II

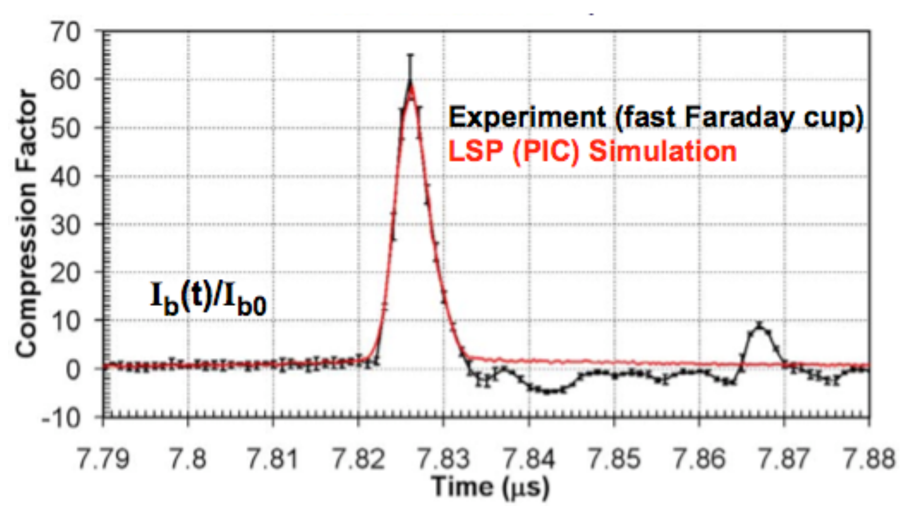
Neutralized drift compression and focusing open up new possibilities

- Eliminating beam's space charge repulsion allows:
  - much shorter pulses
  - a much tighter transverse focus
- Enables near-term Warm Dense Matter studies
- May enable ion direct drive (short range needed -> low K.E. ions -> high I)
- Issues:
  - Background plasma density must be > (or at least =) beam density
  - How to get plasma where it is needed, especially in final focusing solenoid
  - How to prevent plasma from flowing upstream

In NDCX-1, a velocity "tilt" accelerates the beam tail and decelerates the head, yielding ~ 70x pulse compression

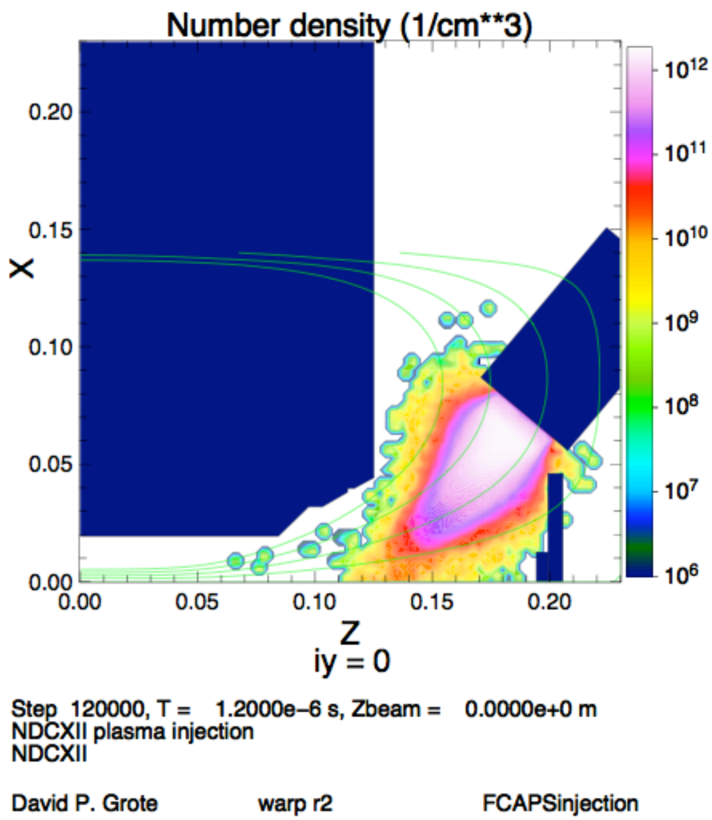




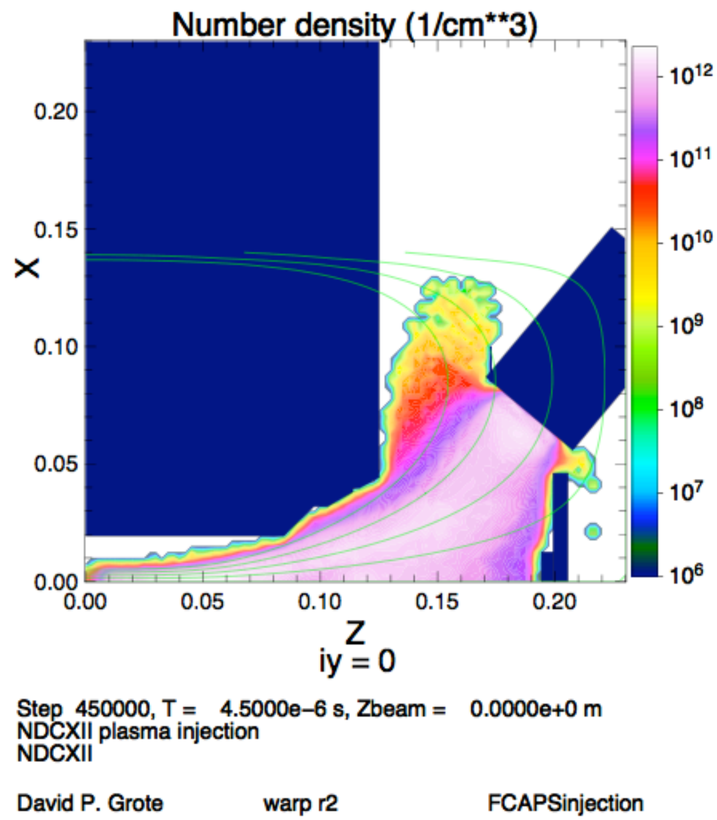


We simulate injection from Cathodic-Arc Plasma sources

1.2 ns



4.5 ns



Here, the Warp code was used; LSP has been used extensively

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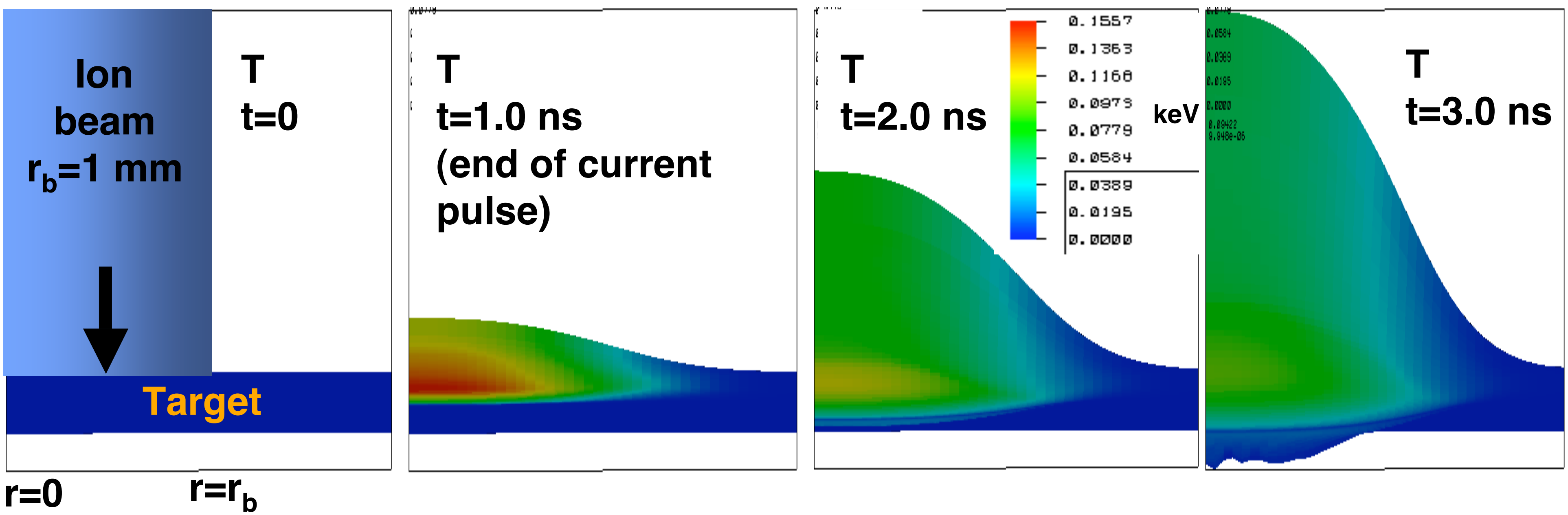
We use the 3D LLNL code HYDRA for target studies

- state-of-the-art multi-physics radiation transport/hydrodynamics code[1]
- Initial explorations of ion beam interactions with foil targets[2]

Illustrative example of non-uniform heating:

2D R-Z, time-dependent simulations of 20 MeV Ne beam hitting 10% Al foam foil

Temperature contour plots



1. M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas 8, 2275 (2001).
2. Simulation collaborators: J.J. Barnard, G.E. Penn, J. S. Wurtele, P. Santhanam, A. Friedman, M. M. Marinak

Talk Outline

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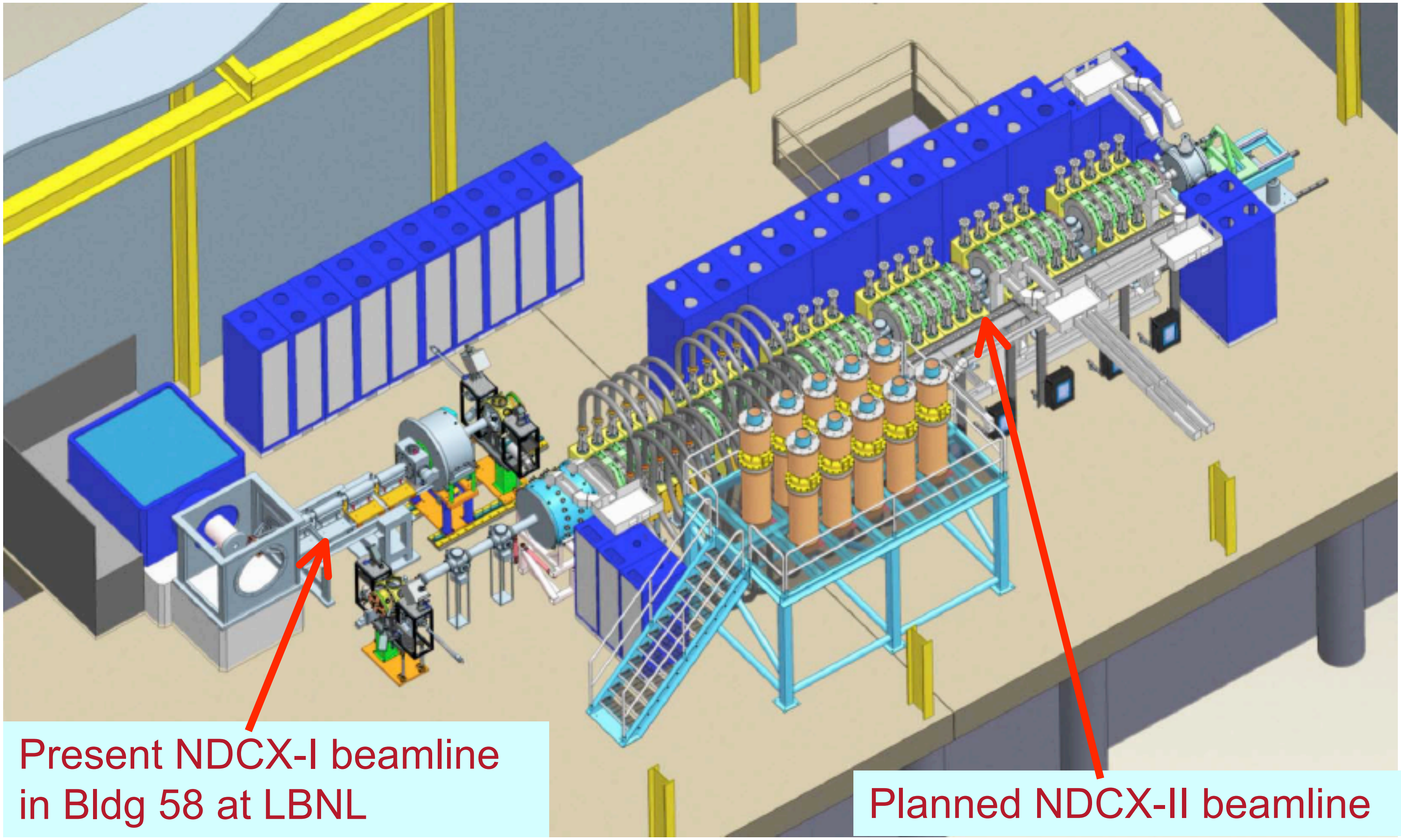
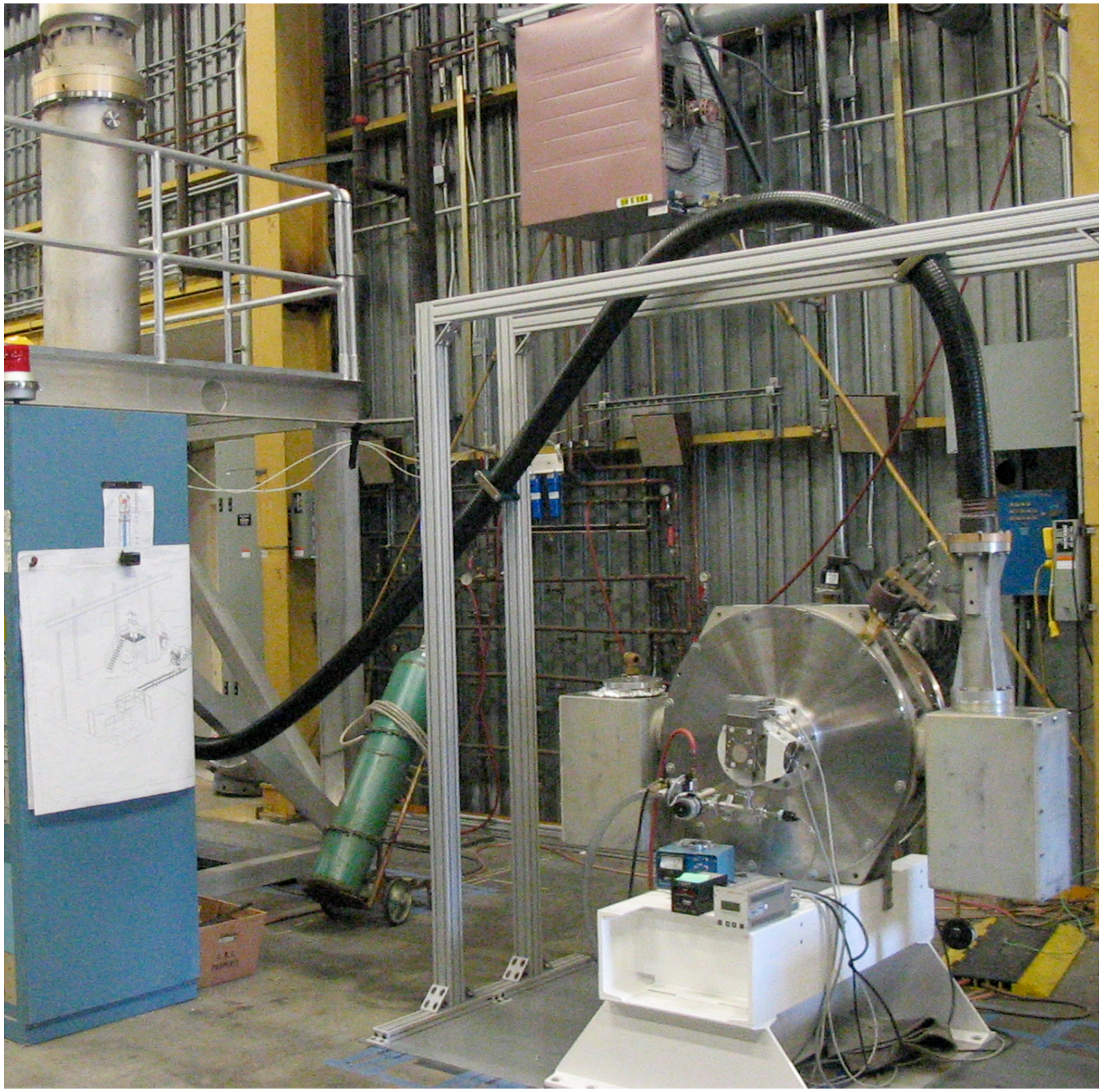
Uniform "Bragg peak"heating of foils, and ion direct drive studies, require a more capable facility than NDCX-I



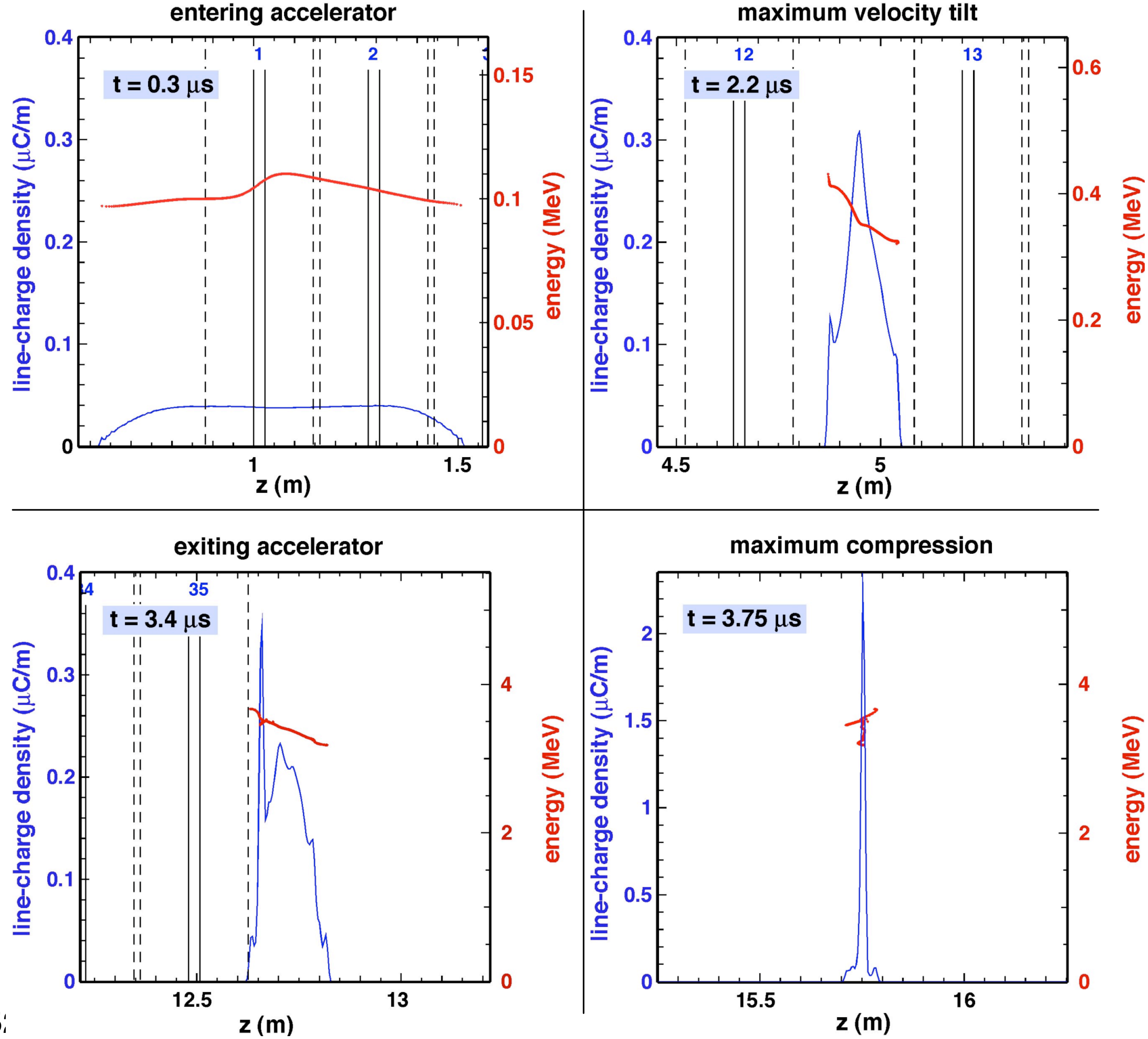
Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility



Test stand has begun to verify performance

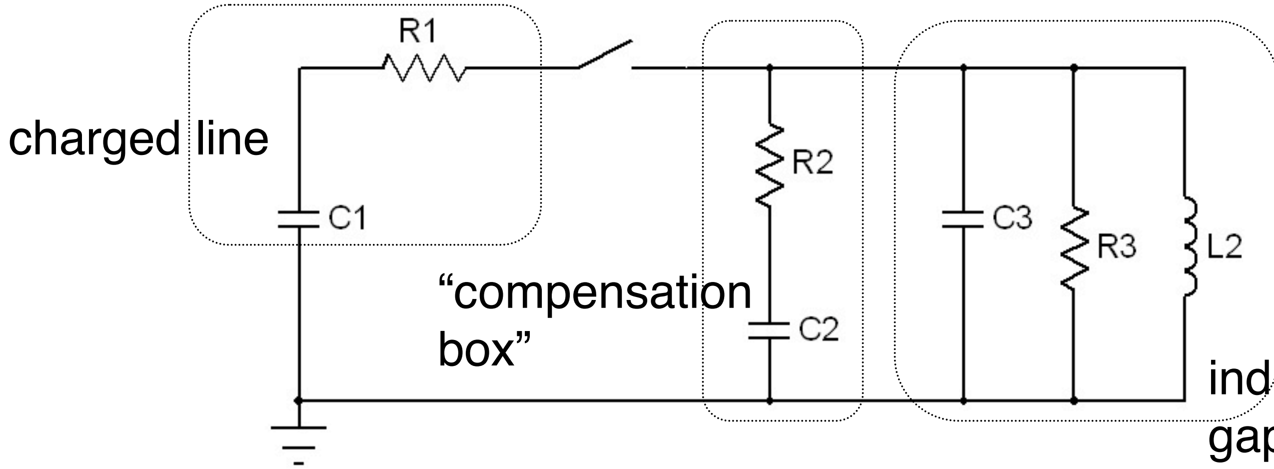
solenoid water cooling

NDCX-II beam's longitudinal phase space is manipulated by pulses from ATA cells, under influence of space charge



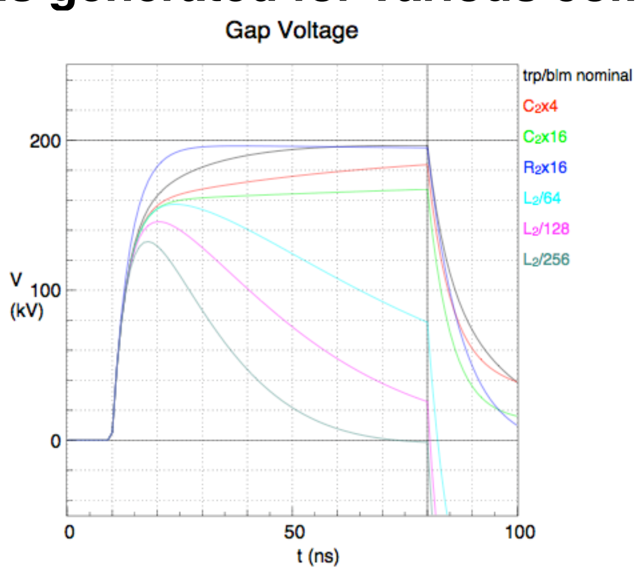
- Note that axis scales change as necessary
- There are few particles in the cross-bar of the final "T–shaped" phase space
- This early example gave a FWHM ~1.6 ns; a shorter and smoother final pulse is expected after tuning

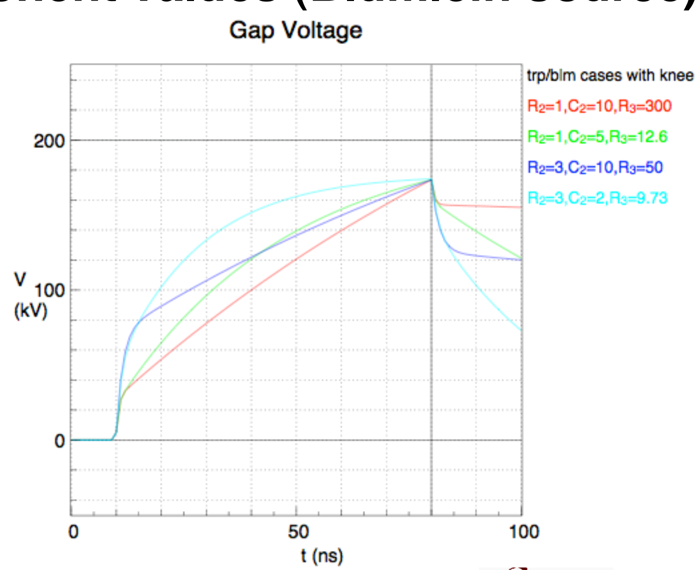
This simple circuit can generate a wide variety of shapes; other equally simple circuits offer additional waveforms



(C3 can be increased, R3 or L2 decreased, by inserting additional components across the cell)

Waveforms generated for various component values (Blumlein source):





CONCLUDING REMARKS …

- Fusion is a (potentially) attractive source of energy
  … but hard to achieve

- Along the way: exciting science to study and technologies to develop

- Computer simulation plays a major role in Heavy Ion Fusion science research

- Kind of courses that are useful for a career in the area: Electromagnetics, Plasmas, Ordinary and Partial Differential Equations, etc.

- For more, visit the UCB Inertial Fusion Energy tutorial at
  http://www.nuc.berkeley.edu/thyd/icf/IFE.html
  and/or the HIFS-VNL web site at
  http://hif.lbl.gov

BACKUP SLIDES

Motivation: energy and climate are coupled concerns

- Oil will be increasingly expensive
  - World oil production will peak in 0 - 30 years
  - Demand will increase due to:

    population

    increasing industrialization & standard of living in 3rd world

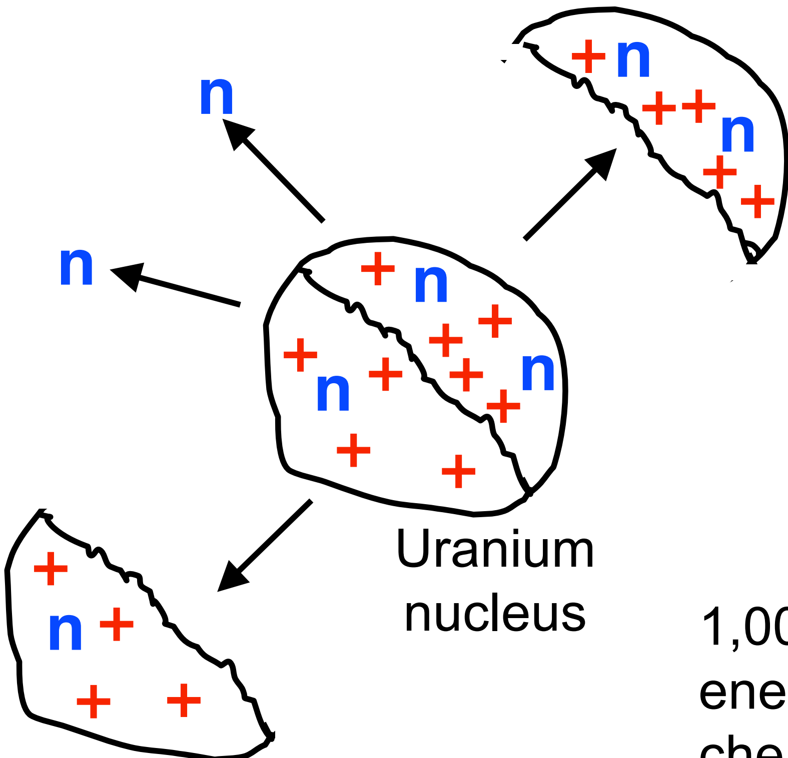
- Natural gas could last ~ 50-100 yrs, and coal 100's of years.

But …

- Global warming, and air pollution, make reliance on coal problematic

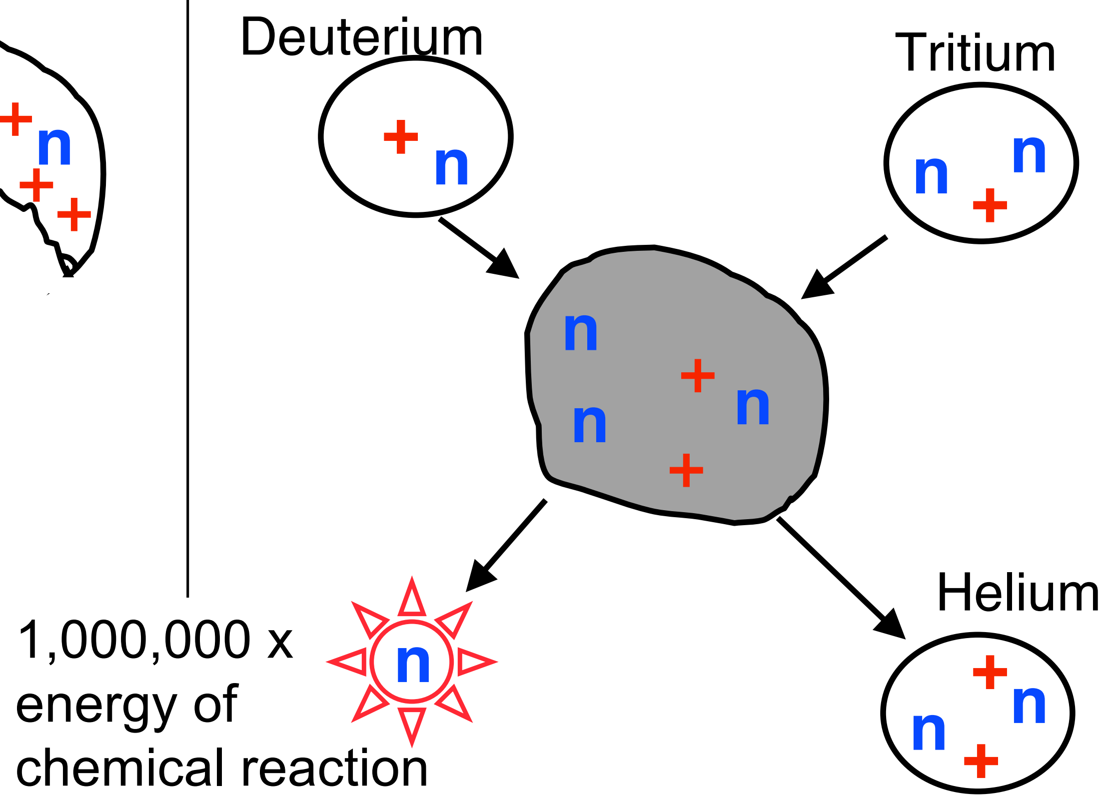
Fission and Fusion

Fission



Splitting a heavy atom
Nuclear power plants, A-bomb

Fusion



Combining light atoms
The sun & stars, H-bomb

Fusion reactions produce lots of energy

When D and T combine to make He, the nuclear force confines them

The new nucleus is in a lower energy state than D + T alone

$\Downarrow$

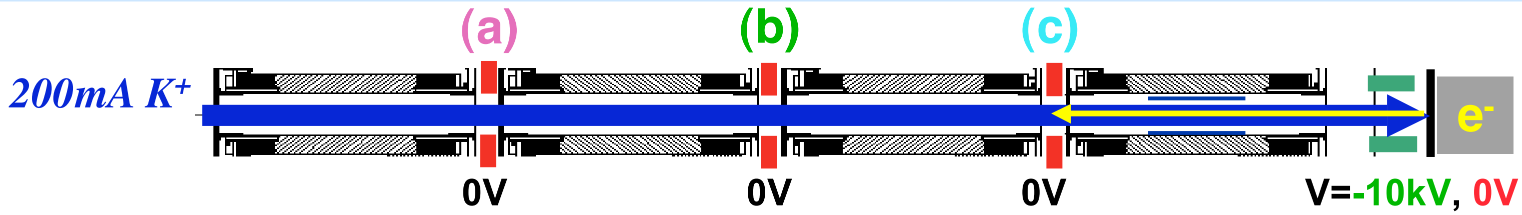
Most of the extra energy is given to the exiting neutron

(Energy out) / (Energy in) = 450

1 gallon of water = 300 gallons of gasoline

(only 0.015% of water is deuterium)

Comparison sim/exp: effects of electrons on beam

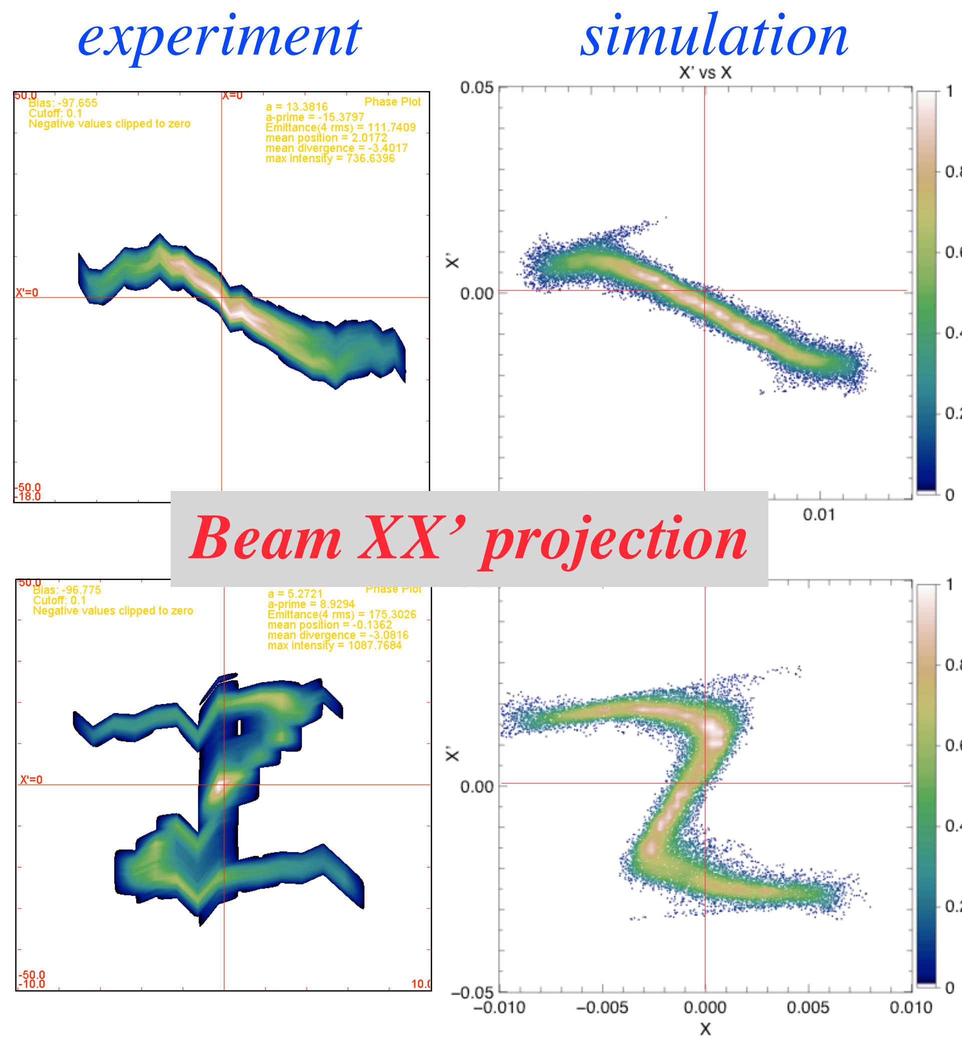


- The electron suppressor is turned ***on*** (V=-10kV) or ***off*** (V=-0V)

Suppressor ***on***

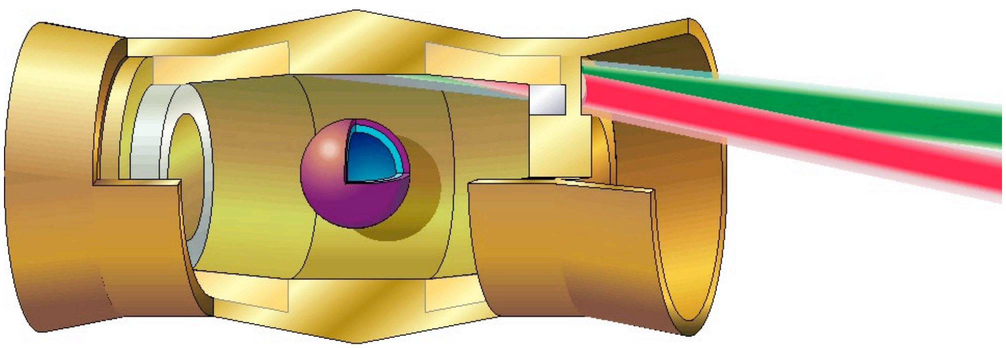
Suppressor ***off***

- Exp./Sim. data agree semi-quantitatively.

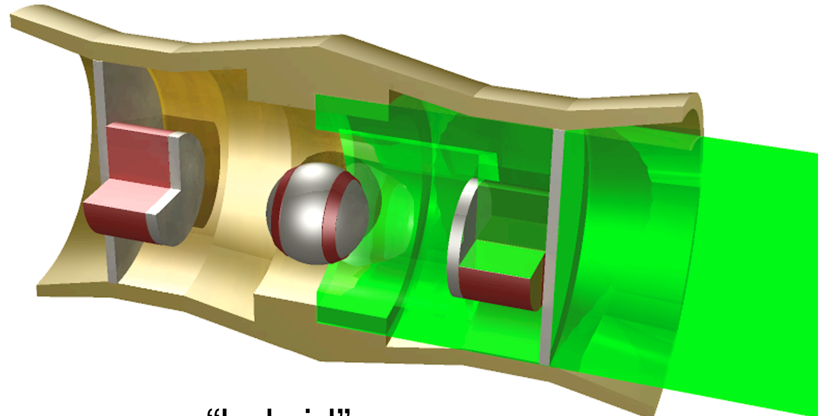


For symmetric illumination, the target is enclosed into a capsule

- Examples of capsule

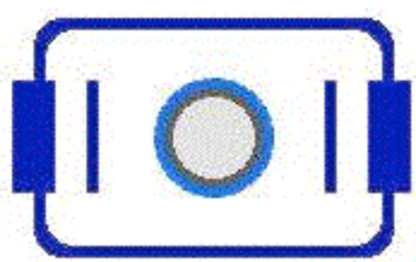


"close coupled"

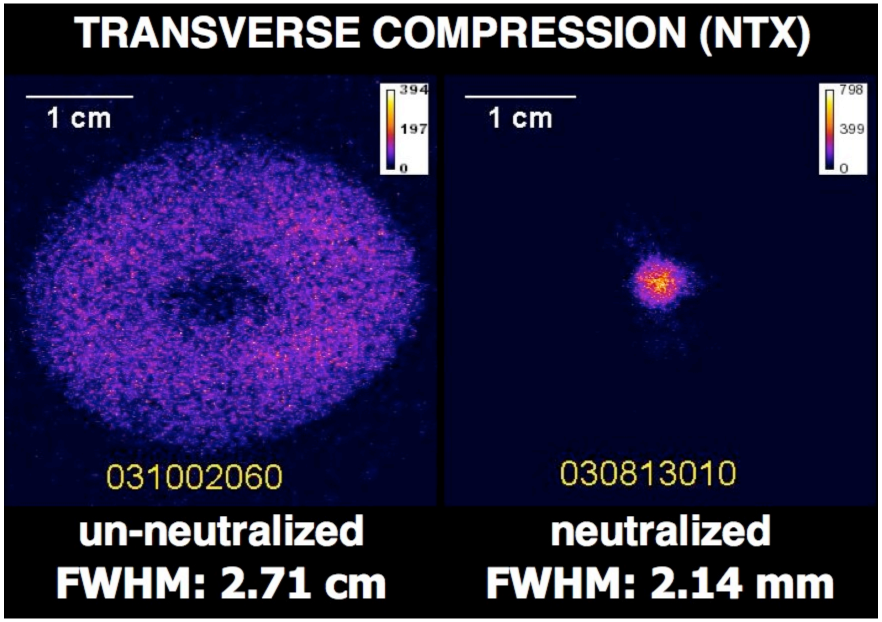


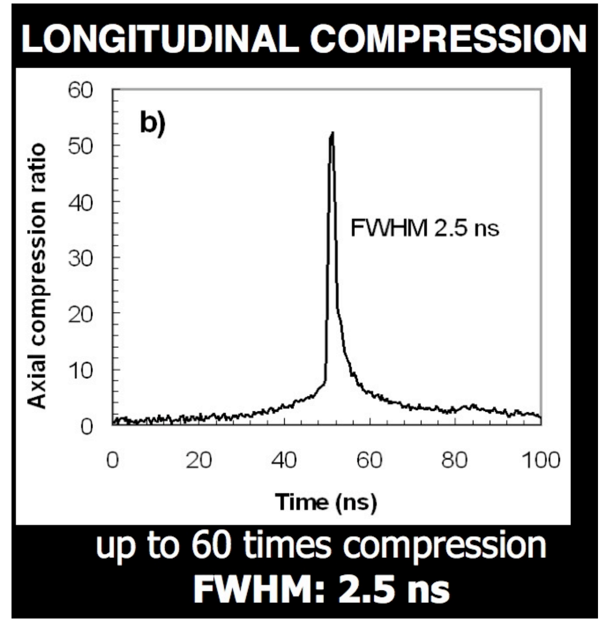
"hybrid"

- Hydrodynamic simulation of target implosion and capsule expansion



NDCX-I, and the earlier Neutralized Transport Experiment (NTX), showed that plasma can cancel a beam's space-charge repulsion





PRL **95,** 234801 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

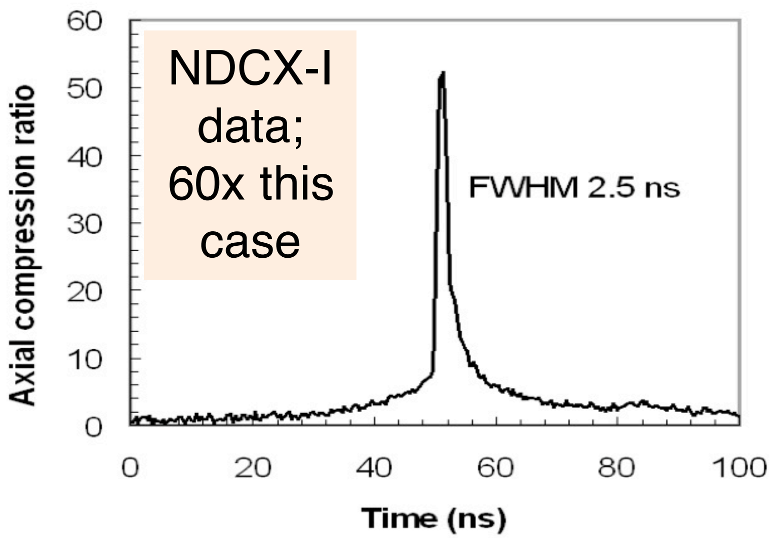
Drift Compression of an Intense Neutralized Ion Beam

P. K. Roy,[1] S. S. Yu,[1] E. Henestroza,[1] A. Anders,[1] F. M. Bieniosek,[1] J. Coleman,[1] S. Eylon,[1] W. G. Greenway,[1] M. Leitner,[1] B. G. Logan,[1] W. L. Waldron,[1] D. R. Welch,[2] C. Thoma,[2] A. B. Sefkow,[3] E. P. Gilson,[3] P. C. Efthimion,[3] and R. C. Davidson[3]

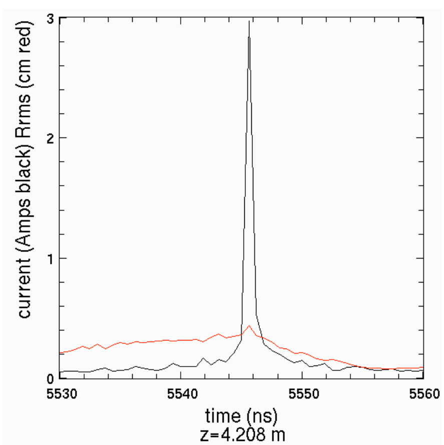
[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California, 94720, USA*
[2]*ATK Mission Research, Albuquerque, New Mexico 87110-3946, USA*
[3]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451, USA*
(Received 9 September 2005; published 29 November 2005)

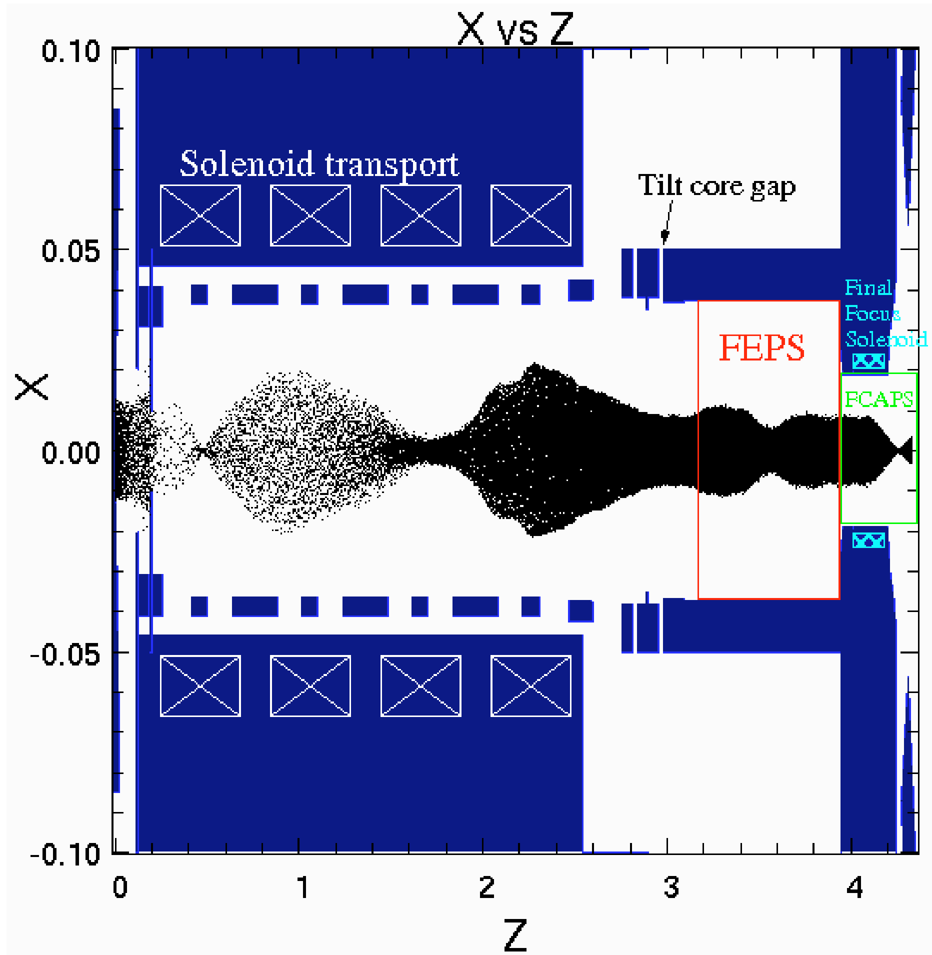
Longitudinal compression of a velocity-tailored, intense neutralized K^+ beam at 300 keV, 25 mA has been demonstrated. The compression takes place in a 1–2 m drift section filled with plasma to provide space-charge neutralization. An induction cell produces a head-to-tail velocity ramp that longitudinally

Experimental data and simulations agree often, but not always (these are difficult problems)



up to 60 times compression



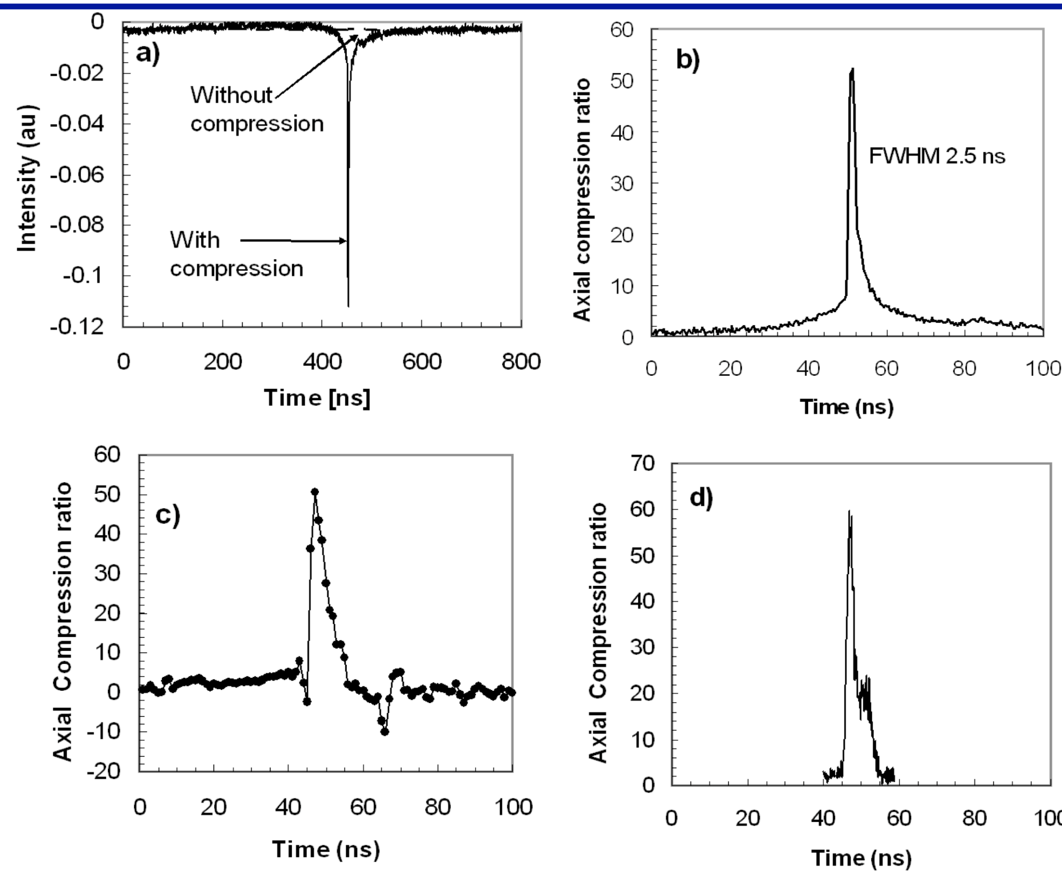


Here, a Warp result is shown; much work has used the LSP code

50-fold* compression measured

Phototube signal with & without compression

Compression ratio Obtained using phototube



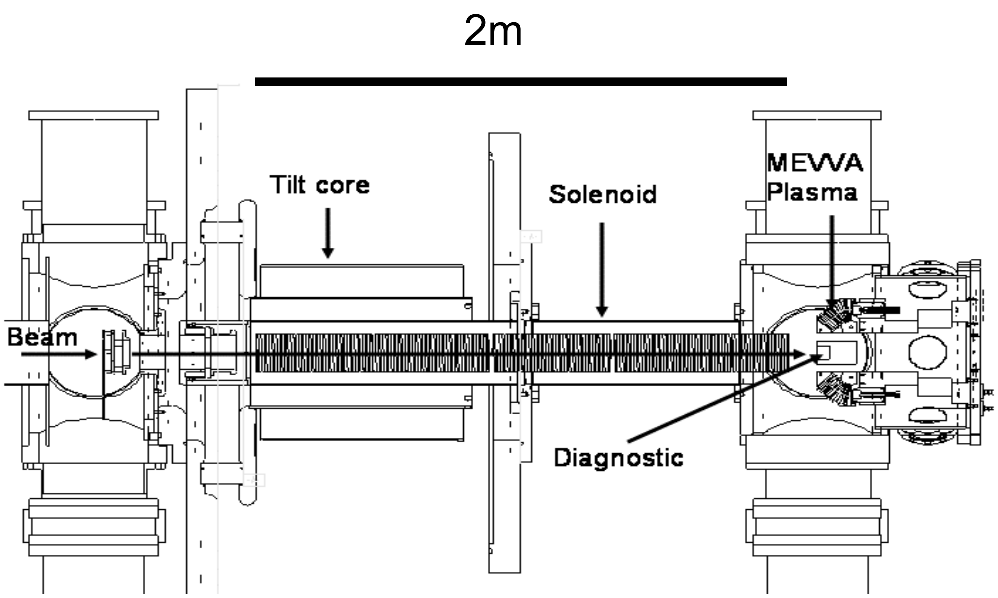
Compression ratio obtained using Faraday cup

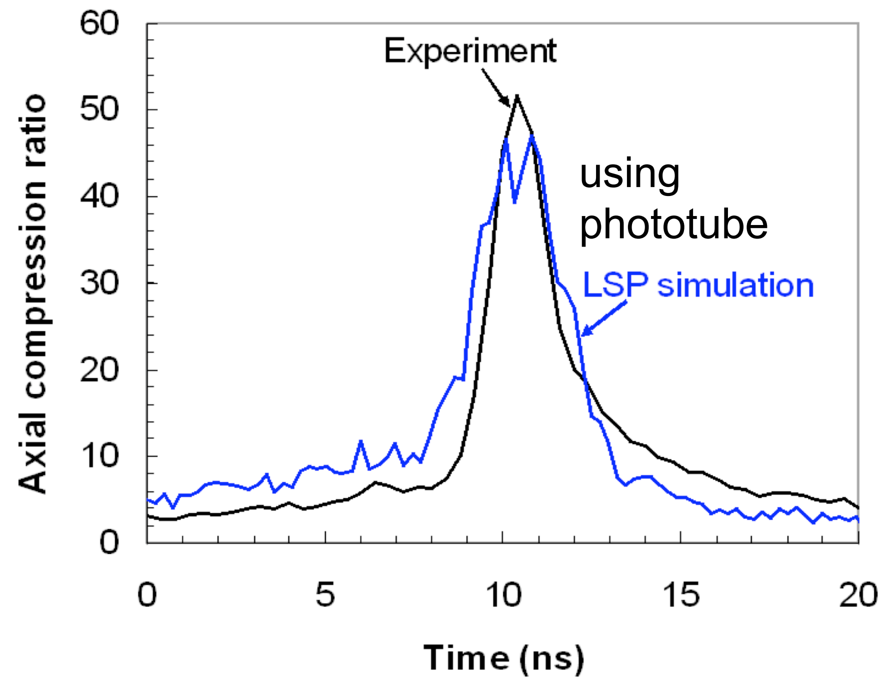
Compression ratio Obtained using LSP simulation

The maximum compression is observed by fine tuning the beam energy to match the voltage waveform and precisely positioning the longitudinal focal point at the diagnostic location.

*Slightly different diagnostic and data reduction yield a factor of 60

Beam stability test with 2-m drift section





- As the drift length is increased, the compression is more sensitive to:
  - -the degree of neutralization and
  - -intrinsic longitudinal temperature.

- If there are any instabilities, e.g. two-stream, they may become evident with longer drift length.

- Longitudinal beam temperature: ~1eV

- No evidence of two- stream degradation or collective instabilities

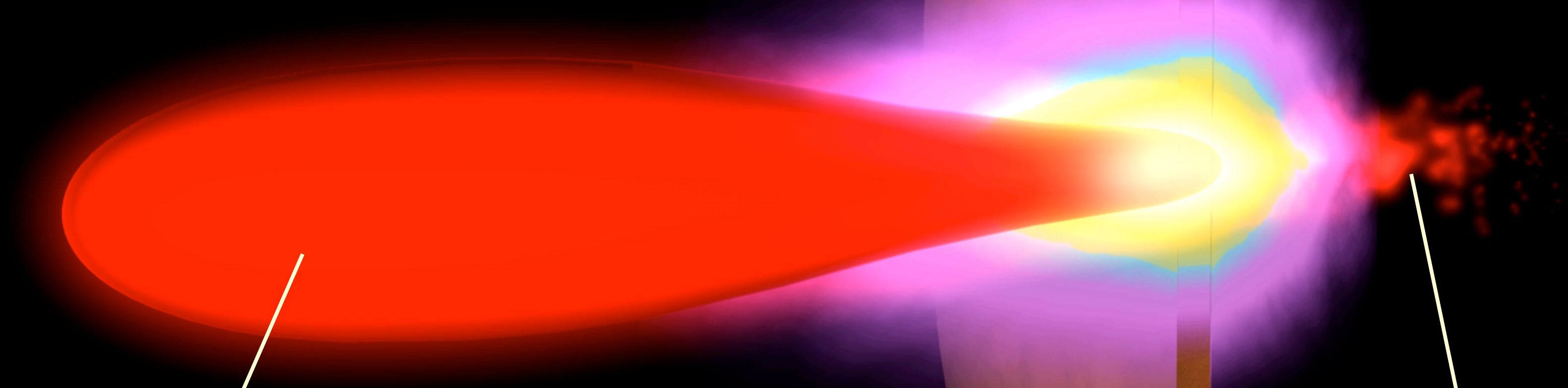
NDCX-II target concept, and driver requirements for > 1 eV

ALUMINUM TARGET FOIL

Thickness (for <5% ΔT):

~3.5 micron, solid density foil (range is 5 microns)

~35 micron, 10% solid density foam

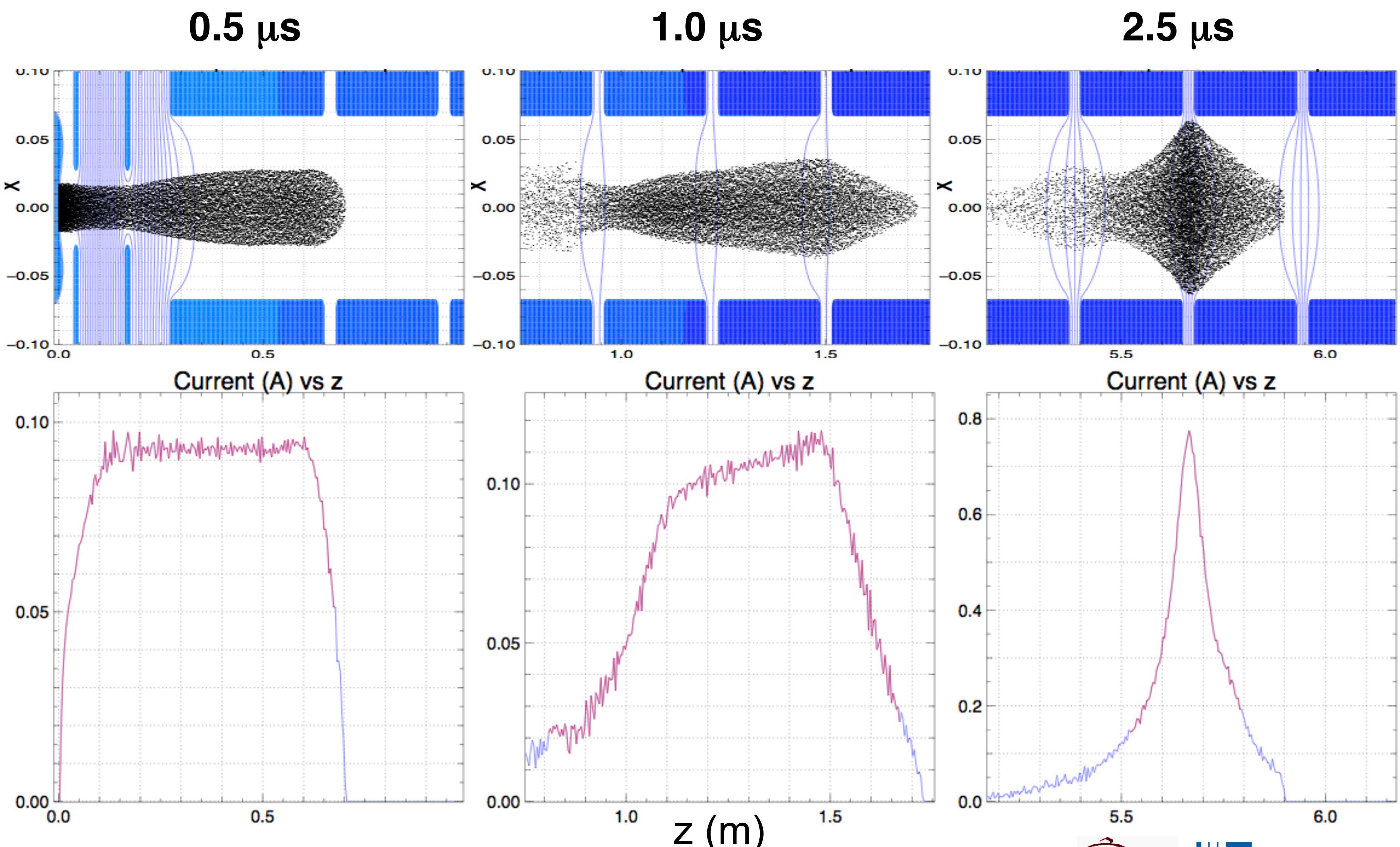


LITHIUM ION BEAM BUNCH

Exiting beam available for dE/dx measurement

Final Beam Energy:	**2.8 MeV**
Final Spot Size :	**<1 mm diameter**
Final Bunch Length:	**<1 ns** ($\cong$ <1 cm)
Total Charge Delivered:	**0.03 μC** (~ 2×10^{11} particles or I_{max} ~ 42 A)
Normalized Emittance:	**0.4 pi-mm-mrad**

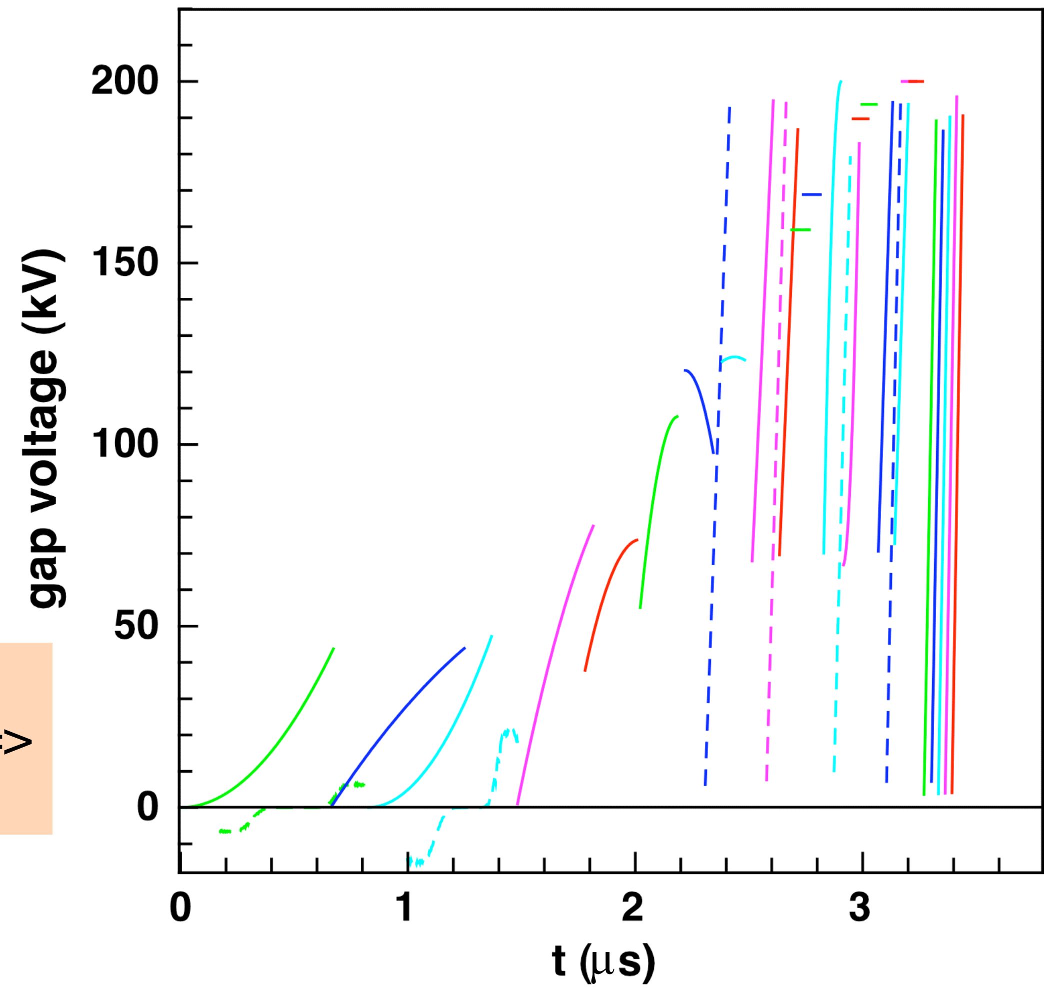
Self-consistent Warp simulations of NDCX-II, from source through “tilt” core, guide the design



NDCX-II will make effective use of assets (accelerating cells and Blumleins) from decommissioned ATA accelerator

- **1-D optimizing code develops waveforms; “spotting scope” for Warp (r,z) runs**
- **The required waveforms are “simple” and can be generated via passive circuits**
- **Warp runs capture beam evolution in realistic self-consistent fields; output beam to feed into target simulations**
- **Need high longitudinal phase-space density; after neutralized drift compression, beam FWHM ~ 1 ns.**

Typical set of 31 accelerating waveforms for Li beam ==>
(yields 3.4 MeV, 30 nC)



(For further information, contact Alex Friedman, Bill Sharp, or Will Waldron)

The HIF program offers students a broad spectrum of opportunities for thesis research

- Particle beam physics
- Accelerator engineering
  - pulsed power
  - mechanical
- Warm Dense Matter physics
- IFE target physics
- Inertial Fusion engineering
  - target chamber
  - target fabrication
- Systems studies for IFE

- Experiments
- Diagnostics
- Simulation
- Theory

… and mixtures of these

For more information ----
contact me at:

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510-486-5592